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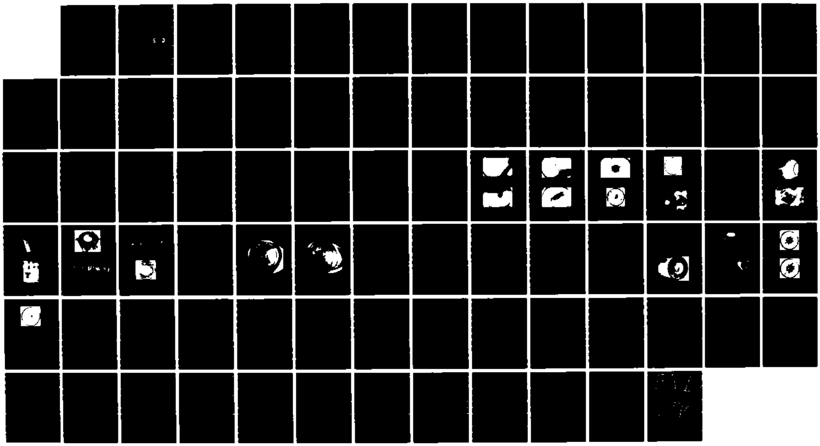

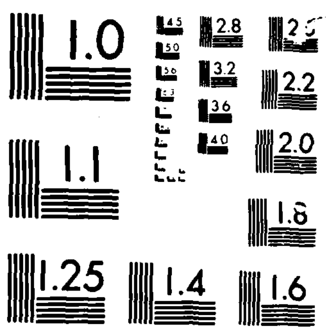

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PRESSURE-RESISTANT PLANE DISC VIEWPORTS FROM ALLYL DIGLYCOL CARBONATE PLASTIC FOR HYPERBARIC CHAMBERS

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The suitability of allyl diglycol carbonate plastic for use as windows in hyperbaric chambers is evaluated. Its resistance to organic solvents, abrasion pitting and radiation appears to make it a better candidate material for this application than acrylic plastic. Problems of production, testing, and the establishment of standards are discussed.

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EXECUTIVE SUMMARY

OBJECTIVE

Acrylic plastic viewports have been used for over 40 years in pressure vessels for human occupancy without any catastrophic failure resulting in a loss of life. However, there are special applications, such as hyperbaric chambers for medical purposes, in which the susceptibility of flex-stressed acrylic plastic to surface crazing and cracking in the presence of common organic solvents contained in antibacterial sprays is a distinct disadvantage. To solve this problem, a search has been initiated for transparent plastics that are not attacked by organic solvents and can be cast economically in thick sections.

APPROACH

Allyl diglycol carbonate plastic appears not only to satisfy the above requirement, but also to provide better resistance to abrasion, pitting, and X-ray or gamma irradiation than acrylic plastic. Short-term, long-term, and cyclic pressure testing has been conducted on over one hundred allyl diglycol carbonate plane disc viewports with t/D_o ratio in the 0.06 to 0.4 range and at temperatures in the +40 to +125°F range.

FINDINGS

It appears that plane discs cast from allyl diglycol carbonate plastic can perform safely as pressure-resistant viewports in pressure vessels for human occupancy. Keywords: Acrylic windows; hyperbaric chambers; Corrosion testing

RECOMMENDATIONS

It is recommended that the design pressure of plane disc windows made from allyl diglycol carbonate plastic not exceed a fraction of their short-term critical pressure (STCP) at an ambient temperature of 75°F. At design temperatures of 75, 100, and 125°F the design pressure of plane disc windows should not exceed 6.5, 5.0, and 3.3 percent of their respective STCPs at 75°F.

CONTENTS

INTRODUCTION

Pressure vessels for human occupancy (PVHO) require viewports in the opaque hulls for their safe operation. In the case of submersibles, diving bells, and personnel transfer capsules, the viewports allow the occupants to observe the wet hydrospace outside the vessel while they remain in a shirt-sleeve environment. A different case presents itself for hyperbaric chambers, in which the viewports permit the chamber operators to observe in comfort the behavior of the personnel inside.

The first use of viewports in such pressure vessels has been lost in antiquity. Reference to their use becomes, however, quite frequent by the 16th century (Reference 1). In almost all cases the viewports consisted of plane glass disc windows seated on leather, cork, or rubber gaskets and held securely in place by steel retaining rings bolted around their circumference to the hull of the pressure vessel.

This state of technology continued until the middle of the 20th century, when glass was replaced by polymethyl methacrylate (acrylic plastic). Acrylic plastic, invented in the 1930's by Rohm and Hass in Germany, made feasible the economical casting of large-diameter, thick windows capable of safely withstanding high pressures. Furthermore, the ductility of the acrylic plastic made the windows fabricated from this material less sensitive to casting imperfections and more resistant to point impacts and dynamic loadings than windows fabricated from glass.

To assure the safe performance of the newly introduced acrylic plastic windows in PVHO's, a safety standard for their design, fabrication, and pressure testing was developed and published by the American Society of Mechanical Engineers in 1977 (Reference 2). With this safety standard, acrylic plastic windows have been designed and successfully operated at pressures in the -15 to +20,000 psi range. Their safety record is outstanding. To date there have been no fatal accidents caused by failure of acrylic plastic windows operated at or below their design pressure and temperature.

One cannot state, however, that there are no operational problems associated with the use of acrylic plastic windows in PVHOs. The acrylic plastic scratches easily, degrades rapidly under X-ray and nuclear radiation, and is very susceptible to stress corrosion crazing and cracking in the presence of organic solvents (Reference 3). In such environments, acrylic plastic windows must be replaced often.

The viewports in hyperbaric chambers used in medical research or for medical treatment are often exposed to organic solvents and subjected to mechanical abrasion during cleaning with disinfectants and germicides. In addition, some of the windows are also exposed to high doses of X-ray radiation during treatment of patients inside the pressurized chambers from a radiation source located outside the chamber and beaming its radiation through the viewport.

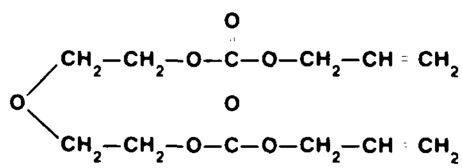
As a result of frequent exposure to solvent in germicides, the acrylic plastic windows exhibit stress-induced crazing on their surfaces that with time grows into a fine network of interconnected cracks. The exposure to X-ray radiation induces gradual discoloration and progressive degradation of the physical properties. The onset of surface crazing, discoloration, and degradation of physical properties decreases the structural performance of the windows to such a degree that they must be replaced. In this hostile environment, the service life of acrylic plastic windows may be shortened to less than a year, whereas in a benign environment, it would be in excess of 20 years.

Because of the expense of frequent replacement of acrylic plastic windows, the Naval Facilities Engineering Command has initiated an exploratory search for a transparent plastic that is more resistant to solvent-induced stress corrosion crazing, abrasion, and radiation than acrylic plastic and yet possesses the optical clarity and structural performance of that plastic. Such a plastic has been tentatively identified as allyl diglycol carbonate, commercially available as CR-39 resin from Pittsburgh Plate Glass Industries (PPGI). This report summarizes the results of an evaluation of allyl diglycol carbonate plastic for service as pressure-resistant windows in viewports for hyperbaric chambers.

BACKGROUND

CHEMICAL CHARACTERISTICS

CR-39 allyl diglycol carbonate, also called "diethylene glycol bisallyl carbonate," is a monomer from which transparent, rigid thermoset plastics can be cast. This monomer has two allylic double bonds in its structure, as shown by the formula below:



The two allylic double bonds make it feasible for the monomer to be polymerized and crosslinked as a unit of homopolymers, or copolymers.

The CR-39 homopolymers are clear and colorless. The monomer is usually catalyzed with 3 percent of benzoyl peroxide (BP) or disopropyl percarbonate (IPP). The polymerization cure typically consists of placing the mix into an air oven or water bath at 70°C for approximately 48 hours. After removal from the mold, the casting is post-cured at 115°C for 2 hours. No water or gases are evolved during polymerization and allylic crosslinking. The resulting thermoset plastic is a rigid, high-strength material with excellent dimensional and optical stability.

The CR-39 copolymers can be formulated by the caster to meet a specific combination of properties, such as improved thermal and chemical stability or the ability to be thermoformed. Typical copolymers with CR-39 are vinyl acetate, methyl methacrylate, and unsaturated alkyd resins.

PROPERTIES OF CAST CR-39 PLASTIC

In the discussion of CR-39, comparisons will frequently be made to acrylic plastic since the properties of that material are well known throughout the industry and it is widely used in structural applications.

The optical transmittance in the visible region is approximately equal to optical glass or acrylic plastic of similar thickness (Figure 1). The index of refraction is just below the refractive index of crown glass (Table 1). Contact with solvents, age, or stress does not cause the plastic to craze or crack readily. The transmittance is not affected by the magnitude of strain to which the plastic is subjected.

Abrasion resistance surpasses that of acrylic plastic, and under certain conditions it approaches that of glass. The Tabor test performed on sheets shows that CR-39 is 30 to 40 times, and glass 2000 to 3000 times, more mar resistant than acrylic plastic. The falling emery test, however, shows that both CR-39 plastic and glass are only approximately 10 times more resistant to surface marring than acrylic plastic (Figure 2).

Impact resistance measured by the standard notched and unnotched Izod specimens is approximately one-half that of acrylic plastic. When measured by the falling steel ball impact test, resistance to fracture initiation surpasses, at low temperatures, that of acrylic plastic. When compared to glass, the impact resistance of CR-39 plastic is superior over the whole temperature range of -80 to +150°F.

Resistance to radiation generated by radioactive materials or X-ray machines is superior to that of acrylic plastic. Compared to acrylic plastic, C-39 plastic requires an approximately 50 times larger dose of radiation to reduce its physical properties by 50 percent. A radiation exposure of 10^8 roentgens produces a 5-percent loss of optical transmittance in CR-39 and a 45-percent loss in acrylic plastic. The outstanding resistance to radiation makes the CR-39 plastic a natural choice for pressure-resistant windows in nuclear laboratories and in medical institutions conducting radiation therapy on patients in a pressurized-oxygen environment.

Chemical and solvent resistance of CR-39 plastic is superior in all aspects to acrylic plastic. Acrylic plastic is soluble in ketones, esters, aromatic hydrocarbons, and chlorinated hydrocarbons (i.e., acetone, ethyl acetate, chloroform, benzene, toluene, methyl ethyl ketone, carbon tetrachloride) and is attacked by alcohol, while CR-39 plastic is not (Figures 3-7). One approach to alleviating this situation is to coat the surfaces of acrylic plastic with transparent, hard, and chemically inert compounds. Unfortunately, commercially available abrasion-resistant coatings provide only limited protection for acrylic plastic against attack by solvents. In some

cases the presence of abrasion-resistant castings has lowered the critical pressure of acrylic windows exposed to solvents (Figures 8 and 9). The CR-39 plastic is attacked (etched) only by concentrated oxidizing acids and alkalies (i.e., sulfuric acid, nitric acid, hydrofluoric acid, hydrochloric acid, ammonium hydroxide, etc.). Weak concentrations of oxidizing acids and alkalies do not attack CR-39 or acrylic plastics.

Because of its resistance to hydrocarbons, weak acids and weak alkalies, the CR-39 surfaces do not craze in their presence when stressed. This allows CR-39 windows to be used in applications where they may be accidentally exposed to such chemicals during their operational lifetime. It is this resistance which makes CR-39 superior to acrylic plastic in applications where the contact with chemicals and solvents presents a real threat to the structural integrity of pressurized acrylic plastic windows. Such applications are, for example, viewports in hyperbaric chambers used for (1) medical research treatment requiring periodic disinfection with strong alcohol-based germicides or (2) industrial pressure testing of equipment used in hydrospace, in which some leakage of hydraulic fluids inside the pressure vessel could be expected during the operation of equipment in a simulated hydrospace environment.

The structural properties of CR-39 plastic casting (Table 1) are somewhat less desirable than those of acrylic plastic (Table 2). At room temperature, its flexural strength, tensile strength, and modulus of elasticity are approximately 30 to 40 percent less than the values for acrylic plastic. The differences in physical properties increase even further at temperatures above 125°F. For example, the short-term flexural strength of acrylic plastic (MIL-P 5425) at 125 and 150°F is 12,000 and 8,000 psi, while for CR-39 plastic it is 5,000 and 3,500 psi, respectively. The tensile and compressive strengths drop off similarly with higher temperatures. For this reason windows fabricated from pure CR-39 plastic will fail at significantly lower pressures than windows of equal thickness fabricated from acrylic plastic. Developmental casting resins CR-39 ITS are, however, being developed by PPGI that promise to increase the thermal stability of plastic castings significantly.

The photoelastic constant of CR-39 (80 psi/fringe/inch of thickness) is significantly lower than that of acrylic plastic. This allows viewing of cast sheets under polarized light to be a sensitive technique for the detection of residual stresses (Reference 7). The high photoelastic sensitivity of allyl diglycol carbonate makes it also a desirable material for construction of structural scale models used in photoelastic investigation of stress magnitude in full-size structures.

DESIGN OF PRESSURE-RESISTANT CR-39 PLASTIC WINDOWS

Proper design of pressure-resistant windows for viewports in pressure vessels requires that all the conceivable loading combinations to which the windows may be subjected during their service lifetime be considered. That includes predictable short-term overpressurizations, long-term and cyclic pressurizations, and in addition, unpredictable dynamic pressurizations, point

impacts, overheating, and excessive clamping forces due to uneven tightening of retaining ring bolts. The stresses generated in the windows by the various loading combinations are generally of a triaxial nature, whose peak values, because of material creep over the service lifetime of the windows, may vary with loading duration and temperature variation.

Because of the difficulties encountered in analytical calculations, many assumptions have to be made about the creep of material. This makes the magnitude of calculated stresses in windows somewhat questionable. For this reason the majority of plastic windows in pressure-resistant viewports have been designed empirically on the basis of published experimental data derived from hydrostatic testing of different window shapes.

The accepted empirical approach to the design of acrylic plastic windows consists of finding (1) an experimentally generated short-term critical pressure (STCP) curve for the desired window shape over a wide range of t/D_i ratios at 75°F ambient temperature and (2) applying the appropriate conversion factor to the chosen design pressure. The conversion factors relate the STCP at 75°F to the design pressure and temperature. The magnitude of the conversion factors is quite large as they must take into account static fatigue, cyclic fatigue, and variation in the physical properties of commercially available plastic in thick sheet or custom casting. The ASME Safety Standard for Pressure Vessels for Human Occupancy (PVHO-1) contains a series of experimentally generated STCP curves for different acrylic plastic window shapes and tables with conversion factors formulated on the basis of extensive operational experience. To date none of the acrylic plastic windows designed on the basis of ANS/AME PVHO-1 has failed in service, proving the soundness of this design approach.

Since the CR-39 cast plastic is very similar in its physical properties to acrylic plastic, the same design approach should be considered for windows fabricated from CR-39 plastic. To accomplish this (1) critical pressure curves have to be experimentally generated over a wide range of t/D_i ratios for different window shapes fabricated from CR-39 plastic; (2) conversion factors have to be developed that relate the critical pressure to design pressures and design temperatures; and (3) a quality assurance standard has to be formulated that will ensure reproducible physical properties in CR-39 plastic castings.

Unfortunately, funds are not available at the present time to generate the critical pressure data for all the window shapes currently being fabricated from acrylic plastic. Yet, an immediate need exists for plastic windows that are resistant to solvent and stress crazing. To satisfy the immediate need, the U.S. Navy Facilities Engineering Command (NAVFAC) has sponsored an exploratory study on plane disc windows machined from cast CR-39 plastic sheets. The remainder of this report summarizes the findings of that study.

EXPERIMENTAL TEST PROGRAM

SELECTION OF WINDOW SHAPES

The plane disc shape was selected for the exploratory study on CR-39 plastic windows because it is widely used, inexpensive to fabricate from commercially available sheets, and lends itself to hydrostatic testing in existing test fixtures (Reference 3). The data generated by hydrostatic testing are also relatively easy to interpret because the plane discs fail only in one mode; i.e., when the tensile strain in the center of the low-pressure face exceeds the maximum strain value at which the plastic material fails under short-term, long-term, or cyclic loading.

FABRICATION OF TEST SPECIMENS

The plane disc windows were machined from H-911 plastic sheets supplied by Homalite Inc. The machining consisted of cutting the discs to specified diameters. No attempt was made to face them off to a specified thickness as this would have made the test specimens significantly more expensive and also would have introduced the surface finish as an additional experimental variable. The surface finish could then vary from one specimen to another, causing specimens of the same thickness to fail at significantly different pressures.

Three different diameters (D_o) were chosen for the plane discs: 7.750, 5.00 and 3.00 inches. The nominal thicknesses of the discs were: 7.75-inch-diameter discs were 0.5, 0.75, 1.0, 1.25 inches; 5.00-inch-diameter discs were 1.0, 1.25, 1.75, and 2.0 inches; and 3.00-inch-diameter discs were 0.25 inch.

TEST ARRANGEMENT

The window test specimens were seated individually for testing in metallic fixtures that provided bearing support to each disc around its edge and also made it feasible to provide a watertight seal on its circumference (Figure 10). The dimensions of the seats were as follows:

7.770/6.28 inches, outside/inside diameters
5.050/4.00 inches, outside/inside diameters
3.020/2.40 inches, outside/inside diameters

The fixtures were designed to provide a 1.25 ratio between the outside and inside diameters of the seat. This is the minimum D_o/D_i ratio allowed by ANSI/ASME PVHO-1 for plane discs of acrylic plastic and was thought to be applicable also to CR-39 plastic windows. Neoprene gaskets were used in all tests. The 3.0-inch-diameter seat was covered with a 0.020-inch-thick gasket, while the 5.00- and 7.75-inch-diameter seats utilized 0.063-inch-thick gaskets. Thicker gaskets were used with larger windows as it was known that the latter deviated more than small windows from an ideal plane surface.

The 3.0-inch-diameter windows were sealed in place with a 0.125-inch-thick neoprene gasket compressed between the edge of the window's high-pressure face and a retaining ring with a 2.4-inch-diameter opening (Figure 11). The 5.0- and 7.75-inch-diameter windows were sealed in the test fixture with a compliant 3M Windo-Weld ribbon (Part No. 08631) squeezed into the annular space between the edge of the disc window and the wall of the seat activity (Figures 12 and 13).

TEST PROCEDURES

The test procedure consisted of (1) placing the neoprene bearing gasket on the window seat in the test fixture, (2) inserting the window test specimen into the seat, (3) sealing the test specimen around its circumference, (4) tightening the window retaining ring, (5) inserting the window test fixture inside the pressure vessels, (6) locking the pressure vessel end closure, and (7) pressurizing the interior of the vessel with tap water. The 3-inch-diameter windows were tested in a vessel that incorporated the test fixture into its structure (Figure 14). The 5- and 7.75-inch-diameter windows were tested by mounting the windows in the end closure of a large pressure vessel (Figure 15). The pressurization was conducted with a hand pump that raised the pressure inside the vessel at the rate of approximately 650 psi per minute. The pressure was increased until the specified pressure was reached or the window failed catastrophically. Temperature of the water was measured immediately before and after short-term pressurization. During sustained pressure testing, the temperature was measured at the initiation of the test and daily thereafter.

For some of the tests the window test specimens were instrumented at the center of their low-pressure face with electric resistance straingages and the strains were recorded during pressurization. At the conclusion of each test, the failed window test specimens were removed from the test fixture and photographed.

TEST RESULTS

Short-Term Pressurizations

Short-term pressurizations were conducted until catastrophic failure of the window test specimens took place with a sudden release of pressure (Figure 16). The fracture patterns were similar, if not identical, to those observed previously on plane discs of acrylic plastic (References 4-6, Figures 17 and 18). The thin discs ($t/D_i<0.20$) failed in a typical membrane flexure mode, with cracks radiating from the center of the disc to its edge; the strains at the center of the disc were linear almost to critical pressure (Figures 19 and 20). The thick discs ($t/D_i>0.2$) failed in a typical shear cone mode, with the apex of the cone located at the center of the high-pressure face (Figures 21 and 22). Catastrophic failure of the thick disc was preceded by audible cracking, which generally occurred at approximately 1,000 psi below the critical pressure.

When the STCPs of the plane discs are plotted against their thickness-to-unsupported diameter (t/D_i) ratios, a critical pressure curve is obtained which is very similar to the one for acrylic plastic plane discs, except that the critical pressures of CR-39 plastic discs are consistently lower (Figure 23). The critical pressure for any given t/D_i ratio varied widely; the highest standard deviation for critical pressure was calculated to be 980 psi for a group of discs with a nominal t/D_i ratio of 0.312 and average critical pressure of 4,260 psi.

There were no apparent experimental reasons for this wide variation in STCP of windows with the same t/D_i ratios and D_o. Critical pressures generated by plane discs with different diameters appeared to follow the same relationship between t/D_i ratio and critical pressures. This would seem to indicate that the strength of CR-39 plastic is not a function of the test specimen volume, as is the case for glass. The large variation in critical pressures between specimens of the same t/D_i ratio would seem to indicate, however, a significant variation in physical properties of the many cast plastic sheets from which the windows were machined (Appendix A).

The effect of ambient temperature on the STCP was very significant, but predictable. The critical pressure for thin windows with $t/D_i = 0.104$ varied over 50 percent in the 32 to 125°F range (Figure 24). The decrease in STCP of these thin windows roughly parallels the decrease in flexural and tensile strength of CR-39 over the same temperature range (Figures 25 and 26). Although only a few thick windows were tested at ambient temperatures above or below 75°F, there are indications that the decrease in STCP with temperature increase is similar to thin windows.

Long-Term Pressurization

Long-term pressurization testing was not extensive enough to establish the static fatigue curves for all t/D_i ratios over a broad temperature range. Static fatigue curves were established only for nominal $t/D_i = 0.104$ at 75°F and 125°F ambient environments (Figures 27 and 28). The sustained pressurization data indicate that the static fatigue of CR-39 plastic disc windows under sustained pressure equal to 40 percent of STCP at 75°F is 10^4 minutes in a 75°F environment. For sustained pressure equal to 20 percent of STCP at 75°, the static fatigue is extrapolated to be $>10^8$ minutes in a 75° environment (Figure 27).

At ambient temperatures above 75°F, the static fatigue decreases dramatically. Thus, at an ambient temperature of 125°F, the static fatigue for sustained pressure equal to 40 percent of STCP at 75°F was measured to be 1 minute, and for sustained pressure equal to 20 percent of STCP at 75°F it was measured to be 10^2 minutes. For sustained pressure equal to 10 percent of STCP at 75°F, the static fatigue in 125°F environment is extrapolated to be $>10^8$ minutes (Figure 28).

The strain at the center of the low-pressure discs with $0.08 < t/D_i < 0.5$ ratios appeared to be totally elastic at sustained pressures equal to 10 percent STCP at ambient environment in the 70 to 75°F range (Figures 29 and

30). At higher pressures there was noticeable creep that resulted in varying amounts of permanent deformation, whose magnitude was a function of sustained pressure and its duration (Figure 31). The strains on discs under sustained pressure equal to 5 percent STCP at 75°F were found to be elastic in tests in a 125°F ambient environment.

Cyclic Pressurization

Cyclic pressurization testing was not extensive enough to establish the cyclic fatigue curves for all t/D_i ratios over a broad range of temperatures. A cyclic fatigue curve was established only for nominal $t/D_i = 0.104$ at 125°F ambient environment (Figure 32). The cyclic pressurization data indicate that the cyclic fatigue of a CR-39 plastic disc window at maximum cyclic pressure equal to 20 percent of STCP at 75°F is in excess of 2 cycles. At maximum cyclic pressure equal to 4 percent of STCP at 75°F, the cyclic fatigue is extrapolated to be in excess of 10^8 cycles. The typical pressure cycle consisted of 60-minute sustained pressurization followed by 60 minutes of relaxation.

Chemical Stress Corrosion

Chemical stress corrosion testing has shown that methyl alcohol, glycol, acetone, benzene, and methyl ethyl ketone do not initiate crazing on the face of CR-39 plane disc windows that have been subjected to sustained 2,000-psi tensile flexure stress for 60 minutes. Subsequently, when these plane disc windows were tested to failure under short-term pressurization, the STCP was found to be approximately the same as that of plane disc windows not exposed to these solvents.

By comparison, when acrylic plastic plane disc windows with the same t/D_i ratio were subjected to sustained 2,000-psi tensile flexure stress in the presence of ethyl or methyl alcohol, they immediately began to craze (Figures 3-9). When subsequently tested to implosion, the STCP was significantly lower than that of acrylic plastic discs with the same t/D_i ratio that were not crazed by alcohol (Table 3). Similar observations were made of discs formed from stock (ACRIVUE A) incorporating an abrasion-resistant coating (Table 4). These tests provide convincing proof that CR-39 is significantly less susceptible to chemical stress corrosion failure than acrylic plastic.

Surface Imperfections

Scratched disc windows of CF-39 plastic were found to fail at lower STCP than unscratched disc windows. For CR-39 plane disc windows with t/D_i = 0.104, the STCP of specimens notched radially 0.020 inch deep x 0.060 inch wide on the low-pressure face was approximately 77 percent less than that of unscratched specimens at 75°F ambient temperature (Figure 33). Similar scratch tests performed on acrylic plastic plane discs with t/D_i = 0.104 ratio have also shown a decrease in STCP. However, surprisingly enough, the difference between the STCP of scratched and unscratched acrylic plastic discs

was less (approximately 45 percent) than that for CR-39 plastic (Table 5). This certainly would seem to indicate the CR-39 plastic is more notch sensitive than acrylic plastic, and therefore greater care must be exercised not to scratch CR-39 windows during installation and subsequent servicing.

Similar test results were obtained from CR-39 windows abraded with sandpaper. The STCP of CR-39 windows with $t/D_i = 0.104$ decreased 52 percent after they were scratched with 80-grit sandpaper. The STCP of acrylic windows with the same t/D_i ratio and scratches decreased only 28 percent (Table 6). The scratches were generated on the window surfaces by applying a bearing pressure of 2 psi against a 1-inch-square patch of sandpaper being stroked radially four times across the low-pressure face of the window (Figures 34-37). The average STCP of 0.25-inch-thick unscratched windows with t/D_i = 0.104 at 75°F ambient temperature was in the 540- to 580-psi range for both acrylic plastic and CR-39 windows.

It is interesting to note that the STCP of acrylic plastic discs (at 75°F) with $t/D_i = 0.104$ is significantly lowered by the application of hard, brittle, abrasion-resistant coatings like ACRIVUE A even before exposure to solvents (Table 7). This behavior is probably attributable to the fact that the brittle coating cracks at a much lower stress level than acrylic plastic and that these cracks propagate readily into the acrylic plastic base material, causing it to fracture prematurely.

DISCUSSION

The experimental data generated in this exploratory study by pressure testing of plane disc windows and ASTM material test specimens, plus the data provided by the suppliers of CR-39 resin and castings, make a strong case for utilizing CR-39 casting in structural applications where transparency, resistance to chemical corrosion, and resistance to surface scratching are desirable material attributes. This is not to be construed, however, as a finding that cast CR-39 plastic is structurally equivalent to, or superior to acrylic plastic and thus should be used to replace acrylic plastic on a one-to-one basis in all of its current structural applications.

What is really suggested is that CR-39 plastic, because of its outstanding chemical resistance, scratch resistance, good optics, and acceptable mechanical properties, is an acceptable choice for those applications where acrylic plastic, because of its sensitivity to organic solvent, is only marginally acceptable. But before CR-39 plastic windows can be considered for installation in hyperbaric chambers, design and quality control criteria must be developed for structural application of this plastic.

DESIGN CRITERIA APPROACH

The selection of structural design criteria for CR-39 windows has been patterned after the process used for acrylic plastic windows, which yielded the criteria incorporated in ANSI/ASME PVHO-1 Safety Standard. This design

approach requires that there must be available (1) an experimentally generated STCP curve for the chosen window shape in 75°F ambient temperature environment, (2) an empirically derived set of conversion factors that relate the design pressure and temperature to STCP at 75°F ambient environment, and (3) a set of quality control procedures that ensure the conformance of the CR-39 casting to a minimum level of structural performance.

STRUCTURAL CRITERIA

The STCP curve for plane disc windows of CR-39 at 75°F ambient temperature environment has been generated in this study and can be used by the designer in the selection of window thickness, providing he uses for this purpose the lower bound of the failure region. There are, however, no proven, optimized conversion factors and quality control procedures, as they cannot be tightly defined without operational experience with CR-39 windows.

This is the heart of the problem; without the availability of conversion factors, the windows cannot be designed and placed in service, and without the windows in service, there will never accrue a pool of operational experience to draw upon. A similar problem also exists with quality control procedures for the acquisition of properly cured CR-39 castings.

CONVERSION FACTORS

Thus, in order to place the CR-39 windows in service so that they may begin accumulating operational experience, a preliminary set of conversion factors has been formulated by the author. When the design pressure of a window at the maximum design temperature is multiplied by the appropriate conversion factor shown below, the resulting product represents the required STCP of the window at 75°F ambient temperature.

This set of conversion factors is considered to be very conservative and should preclude catastrophic failure of windows due to any unforeseen set of service conditions. The proposed conversion factors are:

CF = 15 for design temperature of 75°F
CF = 20 for design temperature of 100°F
CF = 30 for design temperature of 125°F

The magnitude of the proposed conversion factors provides for (1) static fatigue in excess of 40,000 hours (2.4×10^6 minutes) and (2) cyclic fatigue in excess of 10,000 cycles (each of 240 minutes duration) in the presence of some slight scratches, and minor variation in physical properties of CR-39 castings. In the future, the magnitude of the conversion factors may be increased or decreased as a result of operational experience. No conversion factors are proposed at the present time for design temperatures in excess of 125°F, as the creep of CR-39 material at these temperatures calls for uneconomically thick windows in order to reduce the stresses to acceptable levels.

QUALITY CONTROL PROCEDURES

The proposed conversion factors are more than adequate, providing the physical properties of the CR-39 castings do not deviate significantly from typical values. Since allyl diglycol carbonate monomer can be polymerized and cross-linked either as a homopolymer or copolymer with widely differing physical properties, quality controls have to be developed that, with a minimum of tests, will determine whether a piece of plastic is a fully polymerized homopolymer CR-39 casting.

The difficulty in devising such a quality control procedure lies in the fact that the number of tests to be performed on each casting lot must be minimized to keep the cost of the test procedure within reason. Since there is at present no single set of tests that is accepted by the industry as definitive for the determination of the structural properties in CR-39 castings, the author would like to propose one that addresses itself specifically to structural applications of CR-39 castings in pressure-resistant windows (Table 8).

Each of the castings to be used for the machining of windows would have material coupons cut off from it and tested for the physical properties shown on Table 8. If the measured values of these physical properties meet the specified values of Table 8, the casting is considered to be acceptable for fabrication of windows. The quality control test performed on material test coupons from a single casting could be used to certify not only the particular castings from which they were taken, but also, under special circumstances, an entire lot of castings.

The tests performed according to Table 8 on one sheet casting chosen at random from a lot of cast CR-39 sheets would serve to certify all sheets of the same thickness from that lot, provided the manufacturer positively and permanently identifies each sheet so certified with a lot number. A casting lot is considered here to be a single production run of 2,000 lb or less, poured from the same mix of resin and catalyst made at the same time, and undergoing identical thermal processing from monomer to polymer, i.e., at the same time and in the same oven.

There is a very real possibility that experience will show the specified minimum values of Table 8 to be either too high or too low, and they will have to be adjusted to meet the typical physical properties of castings produced by the industry. But until sufficient experimental data accumulate from the quality control testing of CR-39 plastic castings with different thicknesses, the proposed set of minimum values for the physical properties listed in Table 8 may have to serve as the sole quality control criteria.

The performance of the quality control test on a CR-39 casting for window fabrication will add anywhere from $750 to $1,000 to the total cost of the lot. Since the cost increase due to quality control tests is independent of the lot size, it is to the advantage of the window buyer to order as many windows as possible at one time so that the cost of the quality control tests will be spread over many sheets from the same lot. Even so, the increase in the price of windows due to quality control testing will never be less than 10

percent. This increase in cost should be gladly paid by the pressure chamber fabricator, as it represents inexpensive performance insurance for the windows, whose catastrophic failure may otherwise result in an expensive liability suit due to personal injury or fatality.

Before undertaking the quality assurance tests listed in Table 8, simple hardness tests may be performed on all castings to identify substandard lots and thereby avoid further expense. Hardness tests have been shown to be a reliable indicator of polymerization completion (Figure 38). Only if the results of hardness tests performed at several locations on both sides of a sheet casting show hardness in excess of Knoop 15 or Rockwell M95 is it worthwhile to perform the remainder of the tests called out in Table 8. Furthermore, to check on the uniformity of polymerization in a large lot comprising many sheet castings, each sheet should be tested for hardness at several locations on both viewing surfaces. Sheets whose hardness is found to be less than the value specified on Table 8 should be removed from that lot.

CONCLUSIONS

1. Preliminary test results indicate that CR-39 allyl diglycol carbonate plastic castings in the form of thick plates can be successfully used in the fabrication of plane disc windows 0.25 to 2.0 inches thick for viewports in hyperbaric chambers.

2. The CR-39 plane disc windows have been found to perform satisfactorily under short-term, long-term, or cyclic pressure loading in the 32 to 125°F temperature range when the working pressure was only a small fraction of the STCP.

3. The thickness of any plane disc window fabricated from CR-39 plastic casting for any given design pressure, design temperature, and window seat diameter (D_i) exceeds the thickness of an acrylic window designed for the same set of operational requirements (Reference 4).

4. The physical properties of commercially available CR-39 castings have been found to vary significantly from one lot to another, making it necessary to apply large safety factors in the design of plane disc windows for hyperbaric chambers.

5. The resistance of CR-39 plastic windows to marring and chemical attack by hydrocarbon solvents is superior to that of acrylic plastic windows.

6. Incomplete polymerization of allyl diglycol polycarbonate castings significantly affects their mechanical properties.

RECOMMENDATIONS

1. The manufacturers of CR-39 castings, fabricators of windows, and potential users of CR-39 plastic windows in hyperbaric chambers should pool their technical experience and operations requirements and prepare cost-effective quality control specifications which, with a minimum of tests, will differentiate between structurally acceptable and unacceptable CR-39 castings for window fabrication.

2. The conversion factors proposed in this report should be utilized in the design of CR-39 plane disc windows for man-rated pressure vessels until sufficient operational experience accumulates to serve as a basis for increasing or decreasing their magnitude.

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Table 1. Typical Properties of CR-39 Plastic Castings.

1. Mechanical Properties	
Flexural Strength, (psi)	ASTM D 790
-10°C (14°F)	13,000
0°C (32°F)	9,000
23°C (73°F)	7,500
50°C (122°F)	5,500
70°C (158°F)	3,500
Flexural Modulus, (psi)	ASTM D 790
-10°C	400,000
0°C	375,000
23°C	350,000
50°C	200,000
70°C	130,000
Tensile Strength, (psi)	ASTM D 638
0°C	8,000
23°C	6,000
50°C	2,500
70°C	1,250
Tensile Modulus, (psi)	ASTM D 638
0°C	330,000
23°C	250,000
50°C	93,000
70°C	60,000
Tensile Elongation, (percent)	ASTM D 638
0°C	3.0
23°C	2.5
50°C	5.0
70°C	3.0
Compressive Strength, (psi)	ASTM D 695
0°C	26,000
23°C	24,000
50°C	18,000
70°C	14,000
Compressive Modulus, (psi)	ASTM D 695
0°C	375,000
23°C	300,000
50°C	135,000
70°C	75,000
Compressive Deformation, (percent) at 4000 psi for 24 hours	ASTM D 638
0°C	0.13
23°C	0.40
50°C	3.6
70°C	9.7

Table 1. Typical Properties of CR-39 Plastic Castings. (Contd)

1 Mechanical Properties (continued)		
Impact Strength, (ft-lb/in.)	ASTM D 256	
IZOD, notched, 0°C	0 25	
IZOD, notched, 23°C	0 3	
IZOD, notched, 70°C	0 25	
IZOD, not notched, 23°C	2	
Charpy, notched, 23°C	0 2	
Charpy, not notched, 23°C	3	
Hardness		
Rockwell		M95
Peters		12 4
Barcol (15 seconds)		24
Knoop		15
Shore D		88
Shear, 23°C, (psi), ASTM D 732		4500
Density, (g/cm³), ASTM D 792		1 32
Taber abrasion (X acrylic plastic) ASTM D 1044		30
Bayer abrasion F735		6
Poisson's ratio		0 4
2 Thermal Properties		
Thermal conductivity, (BTU/in./hr ft², °F), ASTM C 177		1 45
Specific heat, (BTU/lb °F), ASTM C 351		0 55
Deflection temperature, (.01 in. at 24 psi), ASTM D 648		180
Flammability; burn rate (in./min), ASTM D 635		1
Thermal expansion, (linear coeff/°C X 10^{-5})		ASTM D 696
-40 to -10°C		7 0
-10 to +25°C		8 7
25 to +50°C		10 7
Self-ignition temperature, °F, ASTM 1929		720
3 Optical properties		
Index of refraction		ASTM D 542
η^B 20 (706 5 nm)		1 4929
η^C 20 (656 3 nm)		1 4956
η^D 20 (589 3 nm)		1 4980
η^E 20 (546 1 nm)		1 5001
η^F 20 (486 1 nm)		1 5040
Dispersion Factor		60
Transmittance, 27 mm thickness (percent)		
Ultraviolet 280 380 nm		58
Visible 400 700 nm		90
Near infrared 700 1100 nm		90
Stress-optical coefficient 23 C		80 psi in

Table 1. Typical Properties of CR-39 Plastic Castings. (Contd)

4. *Electrical Properties*	
Volume resistivity, (megohms-in.), ASTM D 257	4×10^{14}
Surface resistivity, (megohms), at 480 volts DC, 26.5°C, 50% R. H.	3.4×10^{5}
Dielectric Strength, ($V/10^{-3}$ in.) ASTM D 149	354
Dielectric Strength, ($V/10^{-3}$ in.) ASTM D 149	
50-100 cycles	4.4
10^3 cycles	4.2
10^6 cycles	3.6
Dissipation factor, ASTM D 150	
50-100 cycles	6×10^{-3}
10^3 cycles	8×10^{-3}
10^6 cycles	41×10^{-3}
5. Chemical Resistance	
Percent gain in weight after 7 days immersion at 25°C	
Distilled water	0.7
30% H_2SO_4	0.5
3% H_2SO_4	0.7
10% HNO_3	0.7
10% HCL	0.4
10% NH_4OH	0.8
10% NaOH	0.5
1% Na_2CO_3	0.6
2% Na_2CO_3	0.6
1% NaCL	0.6
3% H_2O_2	0.7
95% Ethyl Alcohol	0.1
50% Ethyl Alcohol	0.5
Acetone	0.5
Ethyl Acetate	0.3
Carbon Tetrachloride	0.6
Chloroform	1.5
5% Acetic Acid	0.6
Gasoline	0.1
Oleic Acid	0.2
Benzene	0.7
Toluene	0.6
6. Permeability	
Water vapor transmission rate, 100% RH, 0.021 in. thick, 22°C (g/m² day)	2.5
Oxygen transmission rate, 24°C, 100% O_2, 0.021 in. thick (cc/m² day)	2.9

Table 2. Typical Properties of Acrylic Plastic Castings.

PROPERTY	ASTM Method	UNITS	Average Value for 0.250-in. Thickness(1)
Mechanical			
Specific Gravity	D792-66		1.19
Tensile Strength	D638-67T		
(Rupture)		psi	9,000-11,000
Elongation, Rupture		%	4.0-4.8
Modulus of Elasticity		psi	400,000-500,000
Flexural Strength	D790-66		
(Rupture)		psi	14,000-16,500
Modulus of Elasticity		psi	475,000
Compressive Strength	D695-63T		
(Yield)		psi	18,000
Modulus of Elesticity		psi	400,000-480,000
Compressive Deformation			
Under Load	D621-64		
4000 psi, 122°F, 24 hr		%	0.7-0.8
Shear Strength	D732-46(1961)	psi	9,000
Impact Strength			
Izod Milled Notch	D256-56(1961)	ft-lb/in. of notch	0.35-0.40*
Rockwell Hardness	D785-65		M94-102*
Barcol Hardness	D2583-67		49-51*
Residual Shrinkage(2)	D702-64T		
(Internal Strain)			
Polycast		%	approx. 2
Polycast Mil Spec		%	less than 1
Optical			
Based on Clear Material			
Refractive Index	D542-50(1965)		1.49
Luminous Transmittance	D1003-61		
As Cast			
Parallel			91*
Total			92*
Haze			less than 1*
Luminous Transmittance	D1003-61		
After 1000 hr Accelerated Weathering	D1499-64		
Parallel			91*
Total			92*
Haze			less than 1*
Effect of Accelerated Weathering	D1499-65		
on Appearance			
Crazing			none
Discoloration			none
Warping			none
Ultraviolet Transmission at 320 nm			0
Displacement Factor	D637-50(1965)		50

(1) All values shown are for 0.250-in. thick sheet unless noted otherwise. Asterisked (*) values will change with thickness.

(2) Difference in length and width, as measured at room temperature, before and after heating above 300 F.

Table 2. Typical Properties of Acrylic Plastic Castings. (Contd)

PROPERTY	ASTM Method	UNITS	Average Value for 0.250-in. Thickness[1]
Thermal			
Hot Forming Temperature[2]		°F	290-360[3]*
Deflection Temperature under load (Heat Distortion Temp.)	D-648-56(1961)		
66 psi		°F	230*
264 psi		°F	195-210*
Maximum Recommended Continuous Service Temperature		°F	180-200
Coefficient of Linear Thermal Expansion	D696-44(1961)	in./in./°F	.000042
Cofficient of Thermal Conductivity (K-Factor)	Cenco-Fitch[4]	$\frac{\text{Btu}}{(\text{hr})(\text{sq ft})(^\circ\text{F/in.})}$	1.3[4]
Flammability (Burning Rate)	D635-63	in./min.	1.1-1.3*
Self-Ignition Temperature	D1929-62T	°F	800-860*
Specific Heat at 77°F	DuPont 900[4] Therm. An. Cal.	$\frac{\text{Btu}}{(\text{lb})(^\circ\text{F})}$	0.35
Smoke Density	ASTM D2843		5-27
Electrical			
Dielectric Strength Short-Time Test	D149-64 (1/8-in. thickness)	volts/mil	430*
Dielectric Constant	D150-65T		
60 cycles			3.5
1,000 cycles			3.2
1,000,000 cycles			2.7
Dissipation Factor	D150-65T		
60 cycles			0.06
1,000 cycles			0.04
1,000,000 cycles			0.02
Power Factor	D150-65T		
60 cycles			0.06
1,000 cycles			0.04
1,000,000 cycles			0.02
Loss Factor	D150-65T		
60 cycles			0.21
1,000 cycles			0.13
1,000,000 cycles			0.06
Arc Resistance	D495-61		No Tracking
Volume Resistivity	D257-66	ohms-cm	1.6×10^{16}
Surface Resistivity	D257-66	ohms	1.9×10^{15}

(1) All values shown are for 0.250 in. thick sheet unless noted otherwise. Asterisked (*) values will change with thickness

(2) Unshrunk sheet will shrink in size by approximately 2% and increase in thickness by approximately 4% when heated to forming temperature

(3) Temperature varies with thickness

(4) Not ASTM method

Table 3. Effects of Solvents and Long Term Pressurization on the Short Term Critical Pressure of Acrylic Plastic Windows.

UNCOATED ACRYLIC VIRGIN CONDITION			
SPECIMEN NO	SOLVENT	DEPTH OF CRAZING	STCP, psi
4a1u	none	none	480
4a2u			580
4a3u			560
4a4u			520
4a5u			540
Average			*536
Std. Dev.			38.5

UNCOATED ACRYLIC PRESSURIZED AT 100 psi FOR 10 MIN			
SPECIMEN NO	SOLVENT	DEPTH OF CRAZING	STCP*, psi
1d1	none	none	620
1d2			460
1d3			550
1d4			500
1d5			620
Average			*550
Std. Dev.			63.9

UNCOATED ACRYLIC PRESSURIZED AT 100 psi FOR 10 SEC			
SPECIMEN NO	SOLVENT	DEPTH OF CRAZING, in	STCP*, psi
1a1	MEOH	0.032	350
1a2	MEOH	0.010	420
1a3	MEOH	0.040	410
1a4	MEOH	0.039	400
1a5	MEOH	0.034	300
Average		0.031	*382
Std. Dev.		0.014	55.6

UNCOATED ACRYLIC PRESSURIZED AT 100 psi FOR 2 MIN			
SPECIMEN NO.	SOLVENT	DEPTH OF CRAZING, in	STCP*, psi
1b1	MEOH	0.053	430
1b2	MEOH	0.050	420
1b3	MEOH	0.061	440
1b4	MEOH	0.047	460
1b5	MEOH	0.040	480
Average		0.050	*446
Std. Dev.		0.008	24.1

UNCOATED ACRYLIC PRESSURIZED AT 100 psi FOR 10 MIN			
SPECIMEN NO	SOLVENT	DEPTH OF CRAZING, in	STCP*, psi
1c1	MEOH	0.105	360
1c2	MEOH	0.139	420
1c3	MEOH	0.138	390
1c4	MEOH	0.111	370
1c5	MEOH	0.135	360
Average		0.126	*380
Std. Dev.		0.015	22.8

Table 3. Effects of Solvents and Long-Term Pressurization on the Short-Term Critical Pressure of Acrylic Plastic Windows. (Contd)

UNCOATED ACRYLIC – PRESSURIZED AT 100 psi FOR 10 MIN			
SPECIMEN NO.	SOLVENT	DEPTH OF CRAZING, in.	STCP*, psi
5b1u	isopropyl alcohol	0.119	240
5b2u	methyl alcohol	0.150	360
5b3u	acetone	0.064	160
5b4u	methyl ethyl ketone	0.068	170
5b5u 1	Vandalex 20	0.053	150
5b5u 2	Vandalex 20	0.055	140

UNCOATED ACRYLIC – PRESSURIZED AT 100 psi FOR 60 MIN			
SPECIMEN NO.	DISINFECTANT	DEPTH OF CRAZING, in.	STCP*, psi
6b1u	Viro-Tec	0.129	250
6b2u	Lysol	0.159	220
6b3u	methyl alcohol	0.184	120
6b4u	Staphene	0.126	300
6b5u	Amphyl	0.162	200

Note 1. The disc dimensions are: D_o = 3 in., t = 0.25 in., t/D_i = 0.104
2. MEOH – methyl alcohol, 99 percent pure.
3. STCP* – short-term critical pressure at 75°F of discs after the conclusion of long-term pressurization to 100 psi.
4. The solvents and disinfectants were applied during pressurization only to the low-pressure face of the disc.
5. Virgin condition – as delivered by the fabricator of windows.

Table 4. Effect of Solvents and Long-Term Pressurization on the Short-Term Critical Pressure of Coated Acrylic Plastic Windows.

COATED ACRYLIC – VIRGIN CONDITION			
SPECIMEN NO.	SOLVENT	DEPTH CRAZING	STCP, psi
4b1c	none	none	380
4b2c	– – –	– – –	480
4b3c	– – –	– – –	420
4b4c	– – –	– – –	380
4b5c	– – –	– – –	410
Average	– – –	– – –	414
Std. Dev.	– – –	– – –	40.9

COATED ACRYLIC – PRESSURIZED AT 100 psi FOR 10 MIN			
SPECIMEN NO.	SOLVENT	DEPTH CRAZING, in.	STCP*, psi
5a1c	isopropyl alcohol	0.135	200
5a2c	methyl alcohol	– – –	420
5a3c	acetone	0.012	340
5a4c	methyl ethyl ketone	0.098	160
5a5c	Vandalex 20		failed after 8 min

COATED ACRYLIC – PRESSURIZED AT 100 psi FOR 60 MIN			
SPECIMEN NO.	DISINFECTANT	DEPTH CRAZING, in.	STCP*, psi
6a1c	Viro-Tec	0.117	270
6a2c	Lysol		failed after 18.5 min
6a3c	methyl alcohol	– – –	failed after 25 min
6a4c	Staphene	– – –	420
6a5c	Amphyl	– – –	420

Note 1. The disc dimensions are: D_o = 3 in., t = 0.25 in., t/D_i = 0.104.

2. STCP*. short-term critical pressure at 75°F of discs at the conclusion of long-term pressurization to 100 psi.

3. Coated acrylic plastic discs were machined from Swedlow's ACRIVUE A.

Table 5. Effect of Notches on the Short-Term Critical Pressure of Acrylic Plastic and Allyl Diglycol Carbonate Windows.

UNCOATED ACRYLIC – VIRGIN CONDITION			
SPECIMEN NO.	SOLVENT	DEPTH OF NOTCH	STCP, psi
4a1u	none	none	480
4a2u	– – –	– – –	580
4a3u	– – –	– – –	560
4a4u	– – –	– – –	520
4a5u	– – –	– – –	540
Average			536
Std. Dev.			38.5

UNCOATED ACRYLIC – NOTCHED .010 in. DEEP			
SPECIMEN NO.	SOLVENT	DEPTH OF NOTCH, in.	STCP, psi
10.1.1	– – –	0.010	360
10.1.2	– – –	0.010	360
10.1.3	– – –	0.010	320
10.1.4	– – –	0.010	310
10.1.5	– – –	0.010	280
Average			326
Std. Dev.			34.4

UNCOATED ACRYLIC – NOTCHED 0.20 in. DEEP			
SPECIMEN NO.	SOLVENT	DEPTH OF NOTCH, in.	STCP, psi
10.2.1	– – –	0.020	300
10.2.2	– – –	0.020	280
10.2.3	– – –	0.020	270
10.2.4	– – –	0.020	280
10.2.5	– – –	0.020	280
Average			282
Std. Dev.			11.0

UNCOATED ALLYL DIGLYCOL CARBONATE – VIRGIN CONDITION			
SPECIMEN NO.	SOLVENT	DEPTH OF NOTCH	STCP, psi
01	none	none	515
02	– – –	– – –	670
03	– – –	– – –	640
04	– – –	– – –	400
05	– – –	– – –	380
Average			557

UNCOATED ALLYL DIGLYCOL CARBONATE – NOTCHED 0.020 in. DEEP			
SPECIMEN NO.	SOLVENT	DEPTH OF NOTCH, in.	STCP, psi
06	none	0.020	120
07	– – –	0.020	135
08	– – –	0.020	121
09	– – –	0.020	142
10	– – –	0.020	140
Average			132

Note 1. The disc dimensions are D_o = 3 in., t = 0.25 in., t/D_i = 0.104.
2. The radial notches are 0.060 in. wide and located 45° apart.

Table 6. Effect of Scratches on the Short-Term Critical Pressure of Acrylic Plastic and Allyl Diglycol Carbonate Windows.

UNCOATED ACRYLIC – VIRGIN CONDITION	
SPECIMEN NO.	STCP, psi
4a1u	480
4a2u	580
4a3u	560
4a4u	520
4a5u	540
Average	536
Std. Dev.	38.5

UNCOATED ACRYLIC – SANDED WITH 80 GRIT	
SPECIMEN NO.	STCP, psi
2a1u	400
2a2u	410
2a3u	380
2a4u	380
2a5u	370
Average	388
Std. Dev.	16.4

UNCOATED ACRYLIC – SANDED WITH 150 GRIT	
SPECIMEN NO.	STCP, psi
2b1u	390
2b2u	380
2b3u	400
2b4u	340
2b5u	380
Average	378
Std. Dev.	22.8

UNCOATED ACRYLIC – SANDED WITH 200 GRIT	
SPECIMEN NO.	STCP, psi
2c1u	490
2c2u	420
2c3u	380
2c4u	420
2c5u	420
Average	426
Std. Dev.	39.7

UNCOATED ALLYL DIGLYCOL CARBONATE VIRGIN CONDITION	
SPECIMEN NO.	STCP, psi
01	515
02	670
03	640
04	400
05	380
Average	557

Table 6. Effect of Scratches on the Short-Term Critical Pressure of Acrylic Plastic and Allyl Diglycol Carbonate Windows. (Contd)

UNCOATED ALLYL DIGLYCOL CARBONATE – SANDED WITH 80 GRIT	
SPECIMEN NO.	STCP, psi
06	265
07	225
08	345
09	280
10	280
Average	279

Note 1. STCP – short-term critical pressure of discs at 75°F.
2. The scratches are applied radially to the disc at eight locations with 1-in.-square sandpaper pad applied with 2-psi force.

Table 7. Effect of Hard, Brittle, Abrasion-Resistant Coating ACRIVUE A on the Short-Term Critical Pressure of Acrylic Plastic Windows.

UNCOATED ACRYLIC – VIRGIN CONDITION			
SPECIMEN NO.	SOLVENT	DEPTH OF CRAZING	STCP, psi
4a1u	none	none	480
4a2u	– – –	– – –	580
4a3u	– – –	– – –	560
4a4u	– – –	– – –	520
4a5u	– – –	– – –	540
Average		– – –	536
Std. Dev.		– – –	38.5

COATED ACRYLIC – VIRGIN CONDITION			
SPECIMEN NO.	SOLVENT	DEPTH OF CRAZING	STCP, psi
4b1c	none	none	380
4b2c	– – –	– – –	480
4b3c	– – –	– – –	420
4b4c	– – –	– – –	380
4b5c	– – –	– – –	410
Average		– – –	414
Std. Dev.		– – –	40.9

Note 1. The disc dimensions are: D_o = 3 in., t = 0.25 in., t/D_i = 0.104.

2. STCP: short-term critical pressure of discs at 75°F.
3. Virgin condition: as delivered by the fabricator of windows.
4. Coated acrylic plastic discs were machined from Swedlow's ACRIVUE A.

Table 8. Specified Minimum Properties for CR-39 Plastic Castings.

Test Procedure ASTM	Physical Property	Specified Value
D 639	Tensile ultimate strength	>5000 psi
	Elongation at break	>2 percent
	Modulus of elasticity	>250,000
D 695	Compressive strength	>20,000
	Modulus of elasticity	>290,000
D 621	Compressive deformation	<5 percent
	At 4000 psi and 122°F	
E 308	Ultraviolet transmittance (for 0.5 inch thickness)	≤5 percent
D 702	Visual clarity	Must pass readability test
D 785	Hardness	·M95
	Both sides of sheet 4 places each side	Rockwell

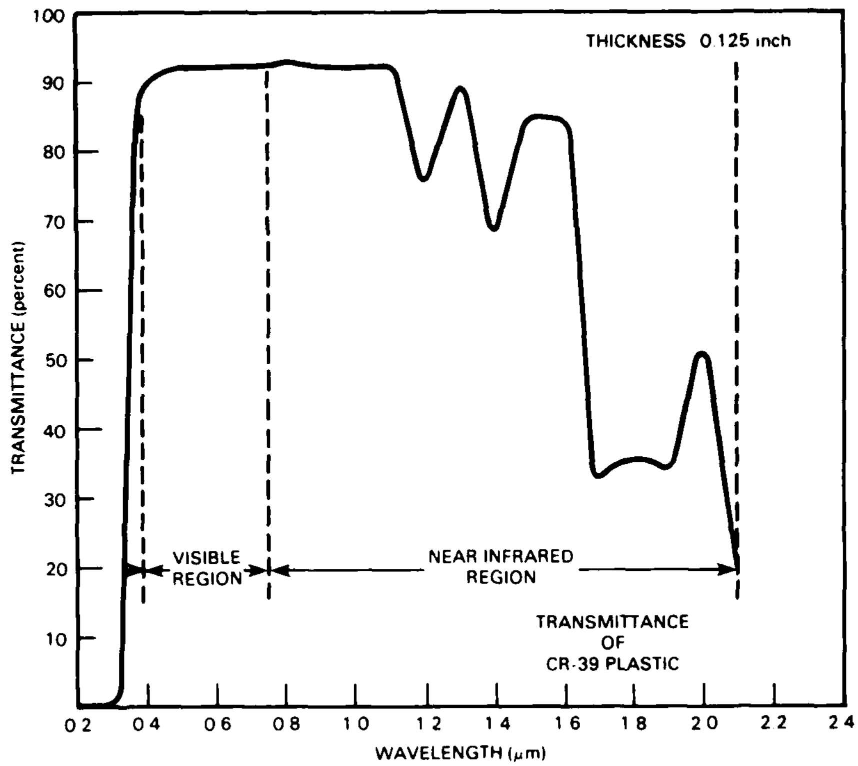

Figure 1. Transmittance of CR-39 plastic casting 0.125 inch thick.

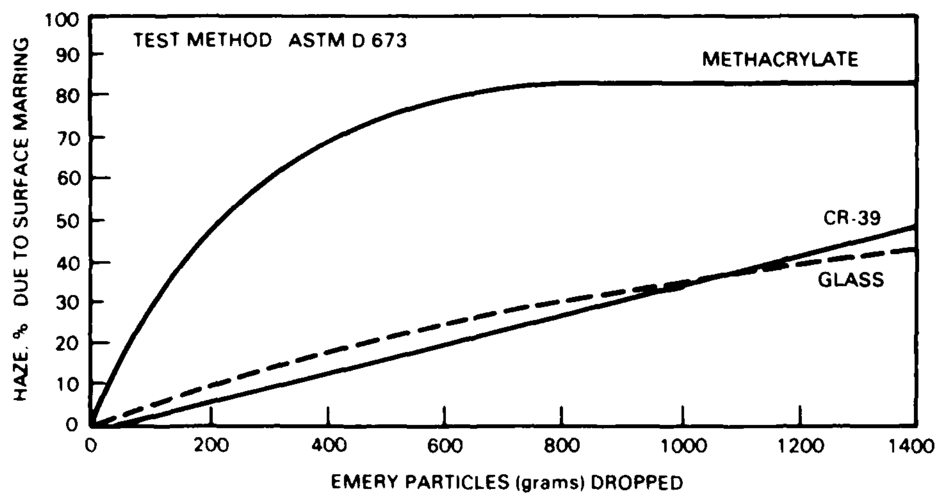

Figure 2. Comparison between scratch resistances of several optical materials.

Figure 3. Crazing of plane disc acrylic plastic window with t/D_i = 0.104 ratio, wetted on the low-pressure face with methyl alcohol while under 100 psi sustained pressure at 75°F ambient temperature; after 10 seconds of sustained loading.

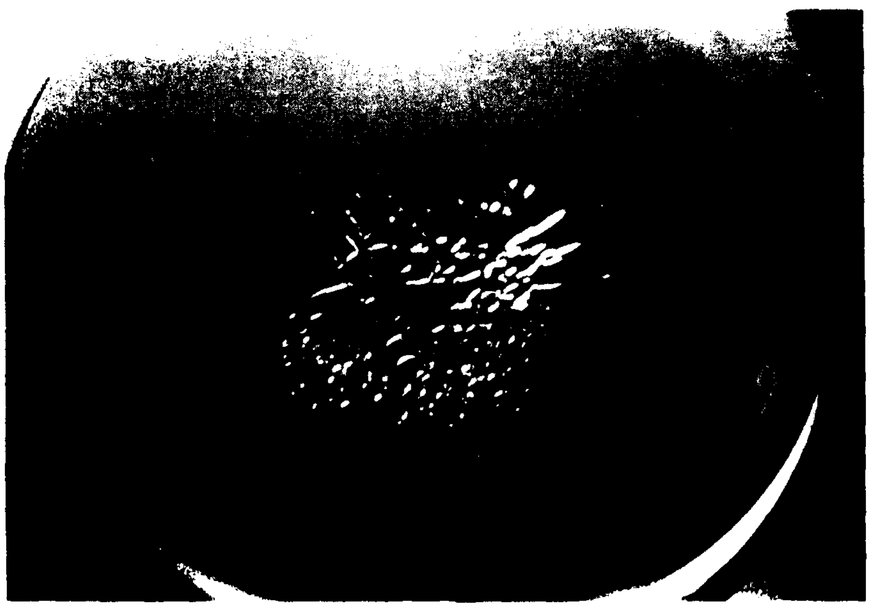

Figure 4. Same window as in Figure 3, but after 30 seconds of sustained loading.

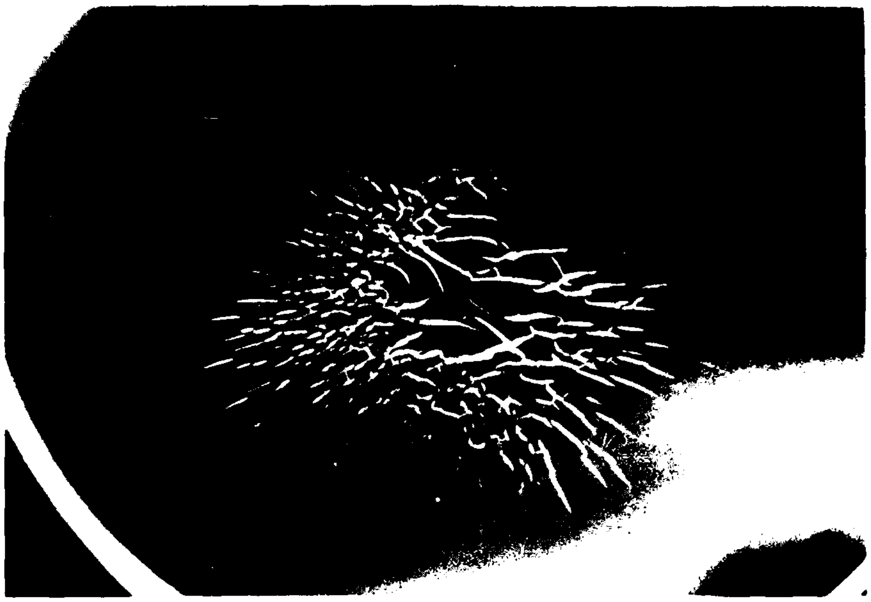

Figure 5. Same window as in Figure 3, but after 120 seconds of sustained loading.

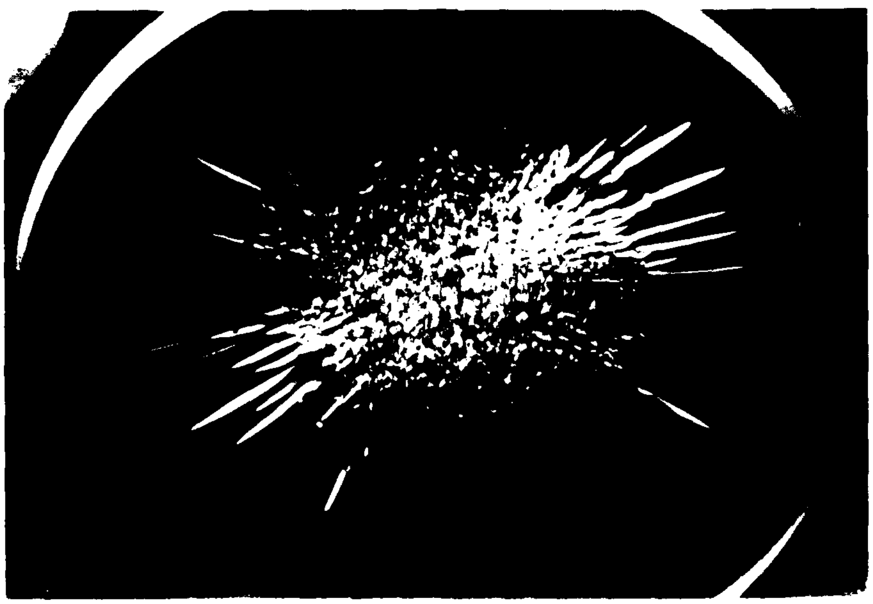

Figure 6. Same window as in Figure 3, but after 600 seconds of sustained loading.

Figure 7. Same window as in Figure 3, but after 60,000 seconds of sustained loading under 100-psi hydrostatic pressure at 75°F ambient temperature.

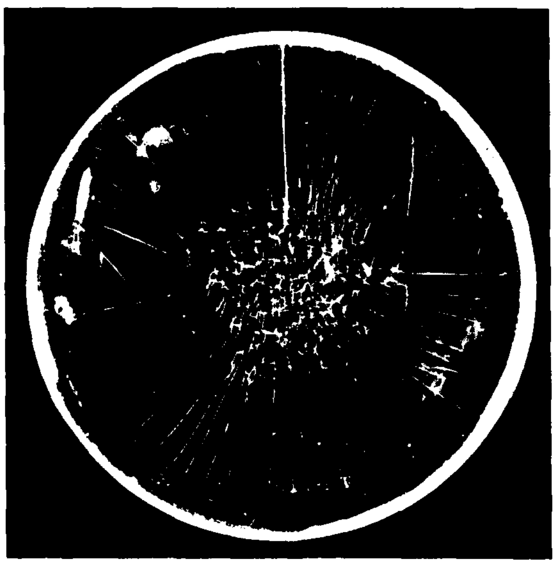

Figure 8. Crazing of plane disc acrylic plastic window with $t/D_i = 0.104$ ratio, wetted on the low pressure face with methyl alcohol while under 100 psi sustained pressure at 75°F ambient temperature after 60 minutes of sustained loading. Depth of crazing 0.18 inch.

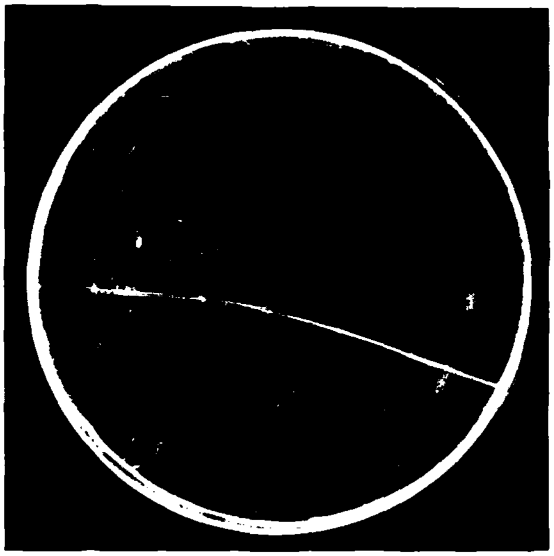

Figure 9. Failed plane disc acrylic plastic window with Acrivue A abrasion-resistant coating. The plane disc window is identical in size and material to the uncoated specimen in Figure 8 and was also wetted with methyl alcohol during pressurization. The failure took place after only 25 minutes of sustained loading under 100 psi pressure at 75°F ambient temperature.

Figure 10. Fixtures used in hydrostatic testing of plane disc windows.

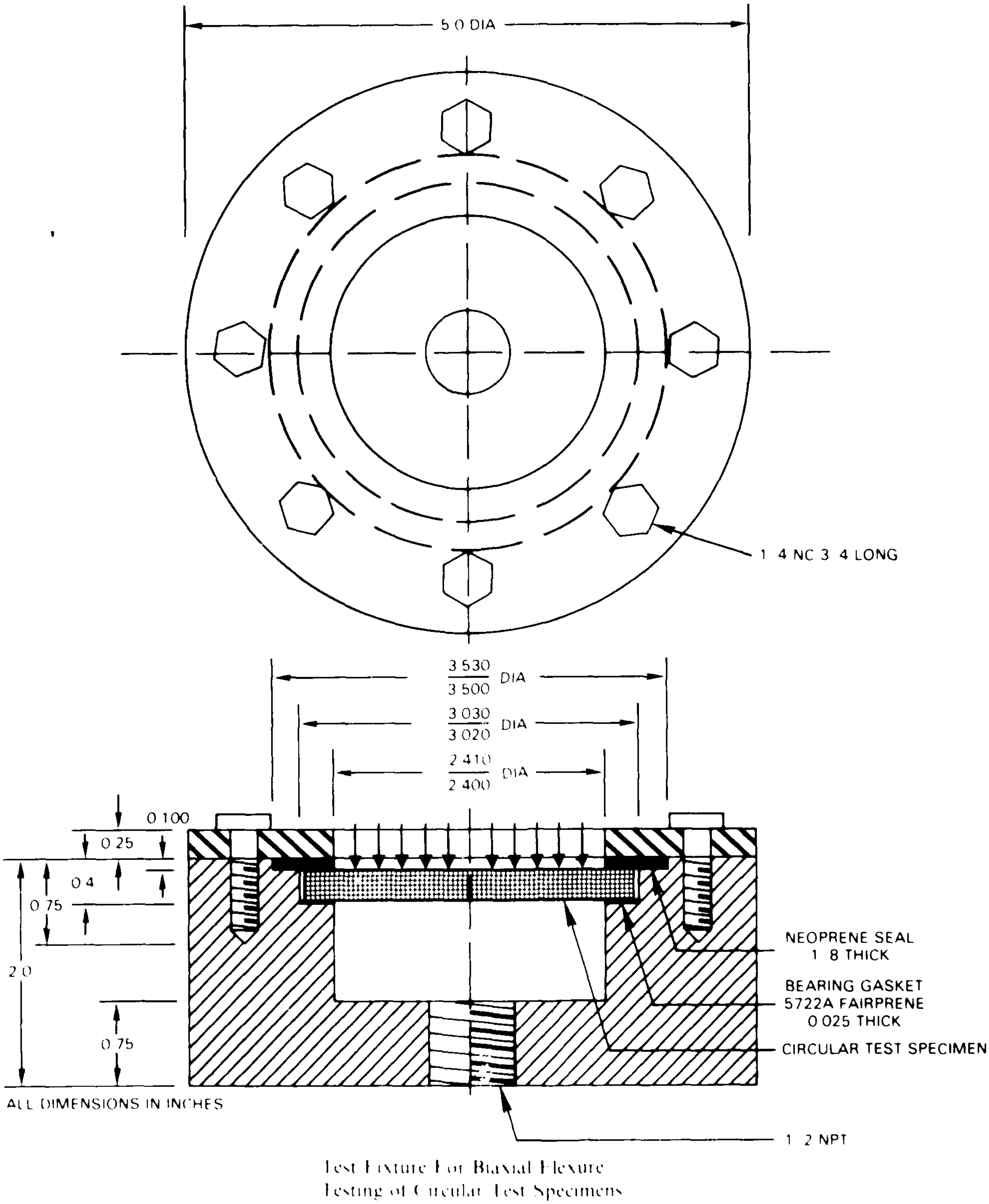

Figure 11. Test fixture for applying biaxial flexure to disc specimen by hydrostatic pressurization method.

Figure 12. Test fixture for 7.75-inch-diameter disc windows.

Figure 13. Sealing of the 7.75-inch-diameter disc window in the test fixture with 3M Windo-Weld mastic tape.

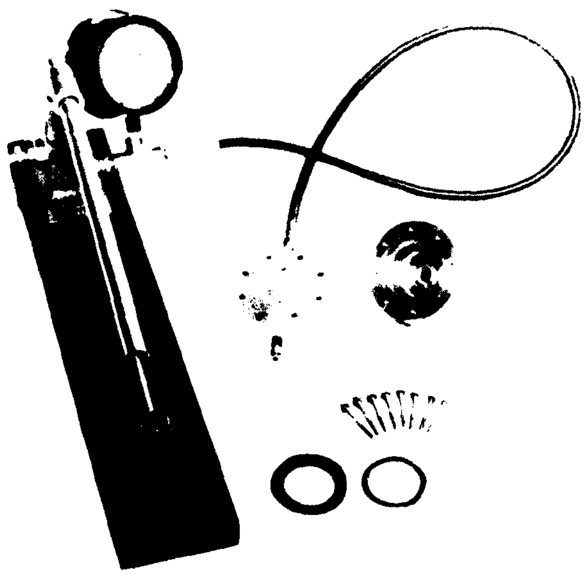

Figure 14. Manually operated pressurization system for pressure testing of 3-inch-diameter disc windows.

Figure 15. Pressure vessel with a 0.75-inch-thick, 7.75-inch-diameter plane disc window mounted in a pressure vessel closure with 6.2-inch-diameter (D_i) opening.

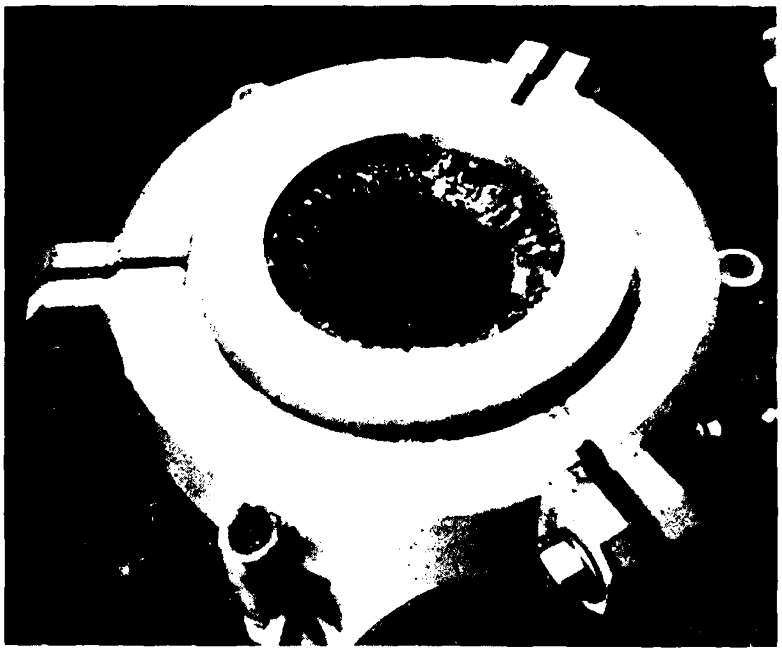

Figure 16. Pressure vessel shown in Figure 15 after catastrophic failure of the plane disc window during hydrostatic pressurization.

Figure 17. Low-pressure faces of 5-inch-diameter allyl diglycol carbonate plastic windows with 1.0-, 1.25-, 1.75- and 2-inch thicknesses after short-term pressurization to failure at 75°F ambient temperature. Note that the diameter of the fracture cone matches the 4-inch opening in the test fixture.

Figure 18. High-pressure faces of disc windows described in Figure 17. Note that the diameter of the penetration through the high-pressure face is inversely proportional to disc thickness.

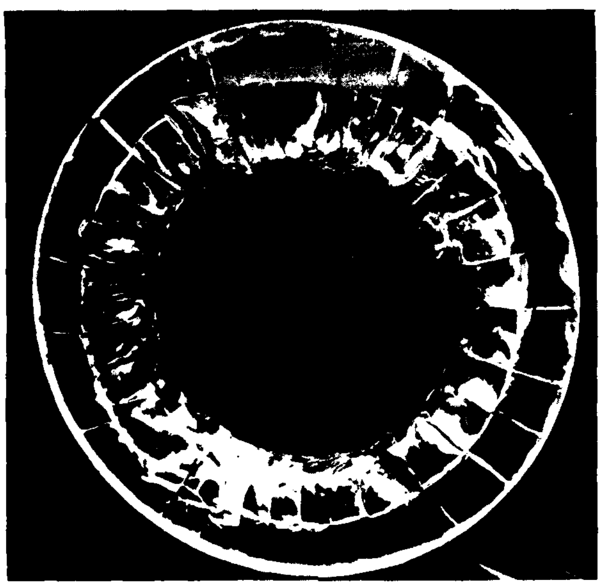

Figure 19. Plane disc CR-39 plastic window with 0.725-inch thickness and 6.2-inch unsupported diameter after catastrophic failure during short-term pressurization to 520 psi at 75°F ambient temperature.

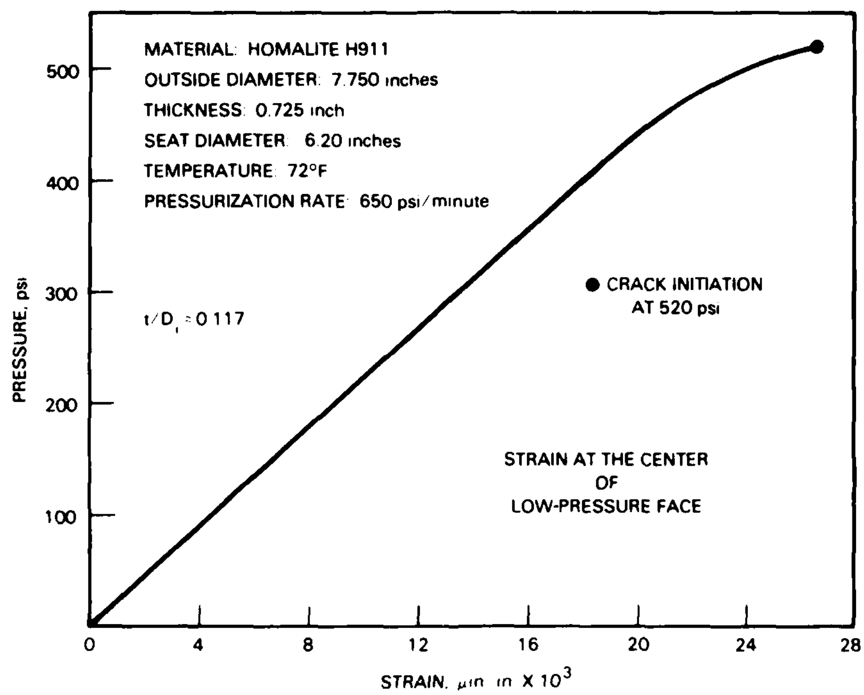

Figure 20. Strain at the center of the low-pressure face on plane disc CR-39 plastic window with 0.725-inch thickness and 6.2-inch unsupported diameter under short-term pressurization to failure at 72°F ambient temperature.

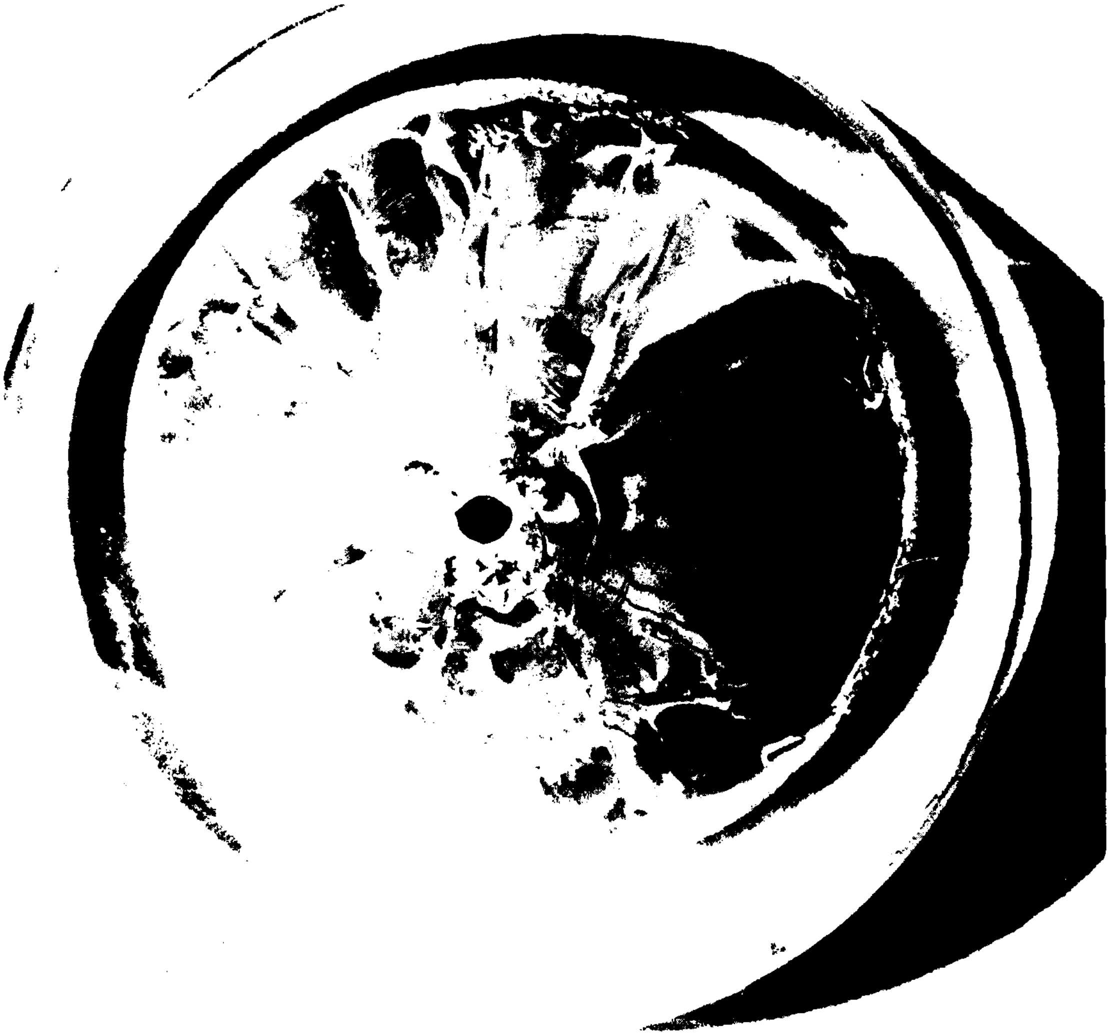

Figure 21. Plane disc CR-39 plastic window with 1.727-inch thickness and 4.0 inch unsupported diameter after catastrophic failure during short-term pressurization at 6500 psi at 125°F ambient temperature; high-pressure face detail.

Figure 22. Plane disc window shown on Figure 21 low-pressure face detail. Note the shear fracture cone, whose apex penetrates the high-pressure face and whose base diameter is defined by the unsupported diameter (D_i) of the window seat in the test fixture.

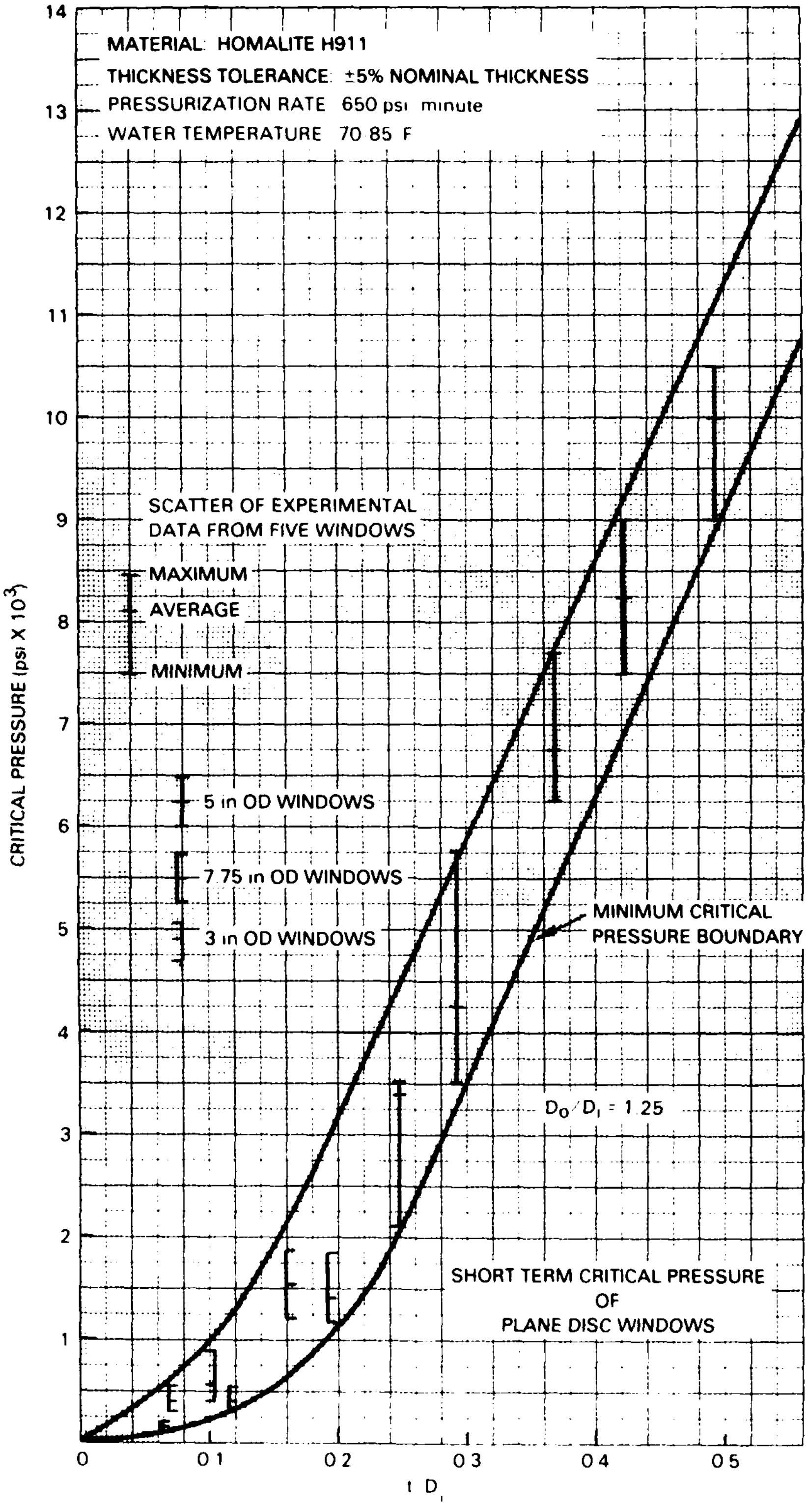

Figure 23. STCP of plane disc CR-39 plastic windows at ambient temperature in the 70-85° F range.

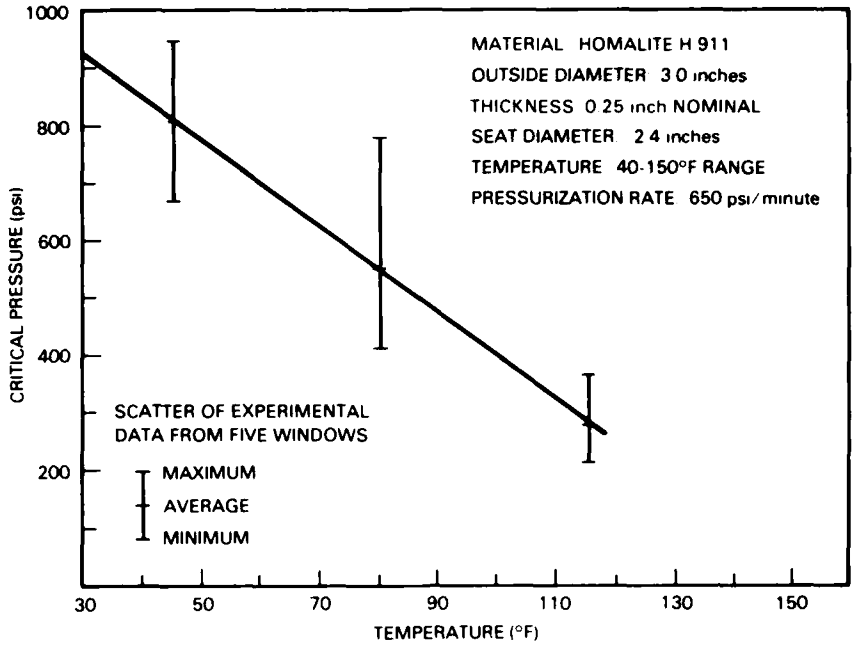

Figure 24. Effect of temperature on the STCP of thin, plane CR-39 discs.

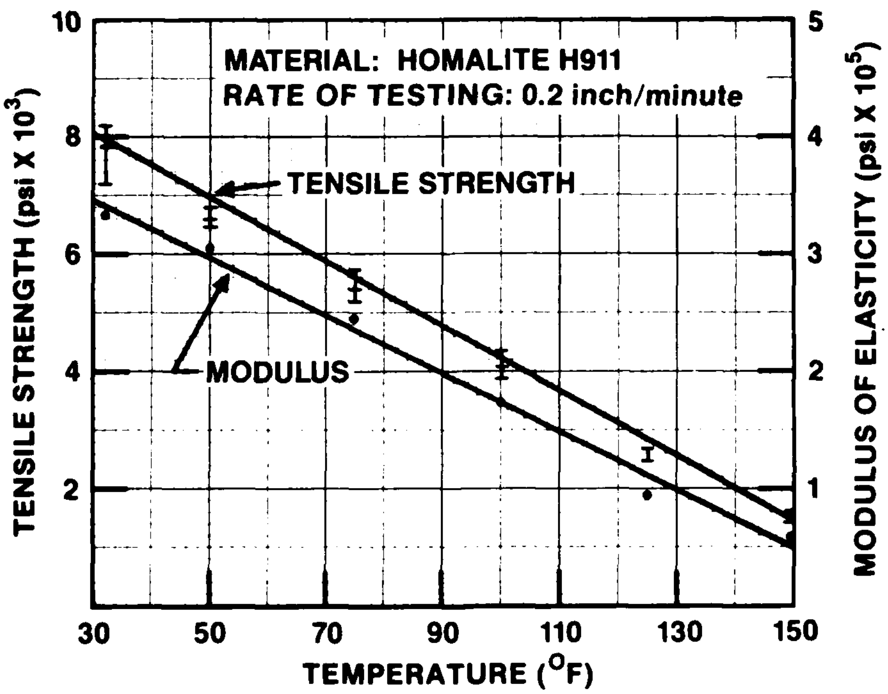

Figure 25. Effect of ambient temperature on the tensile strength and modulus of elasticity in CR-39 plastic under uniaxial tension.

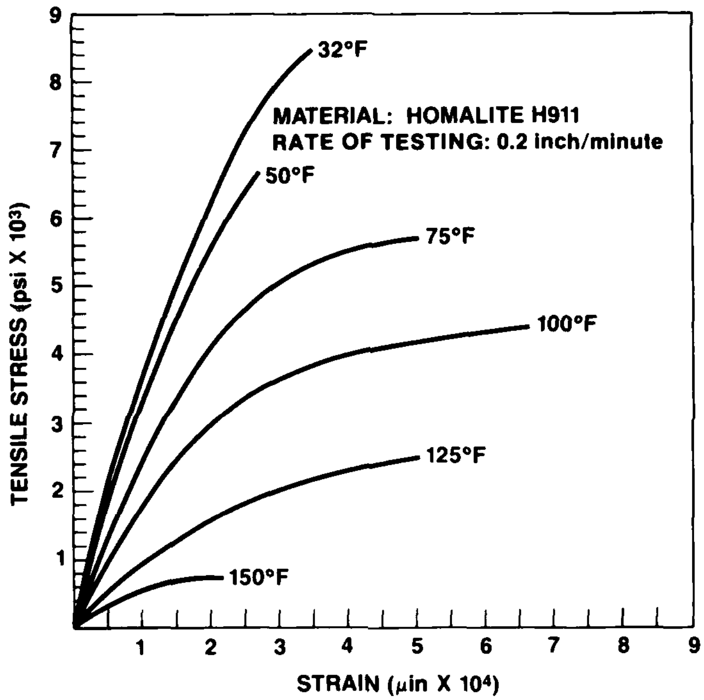

Figure 26. Effect of ambient temperature on the tensile strain in CR-39 plastic under uniaxial tensile loading.

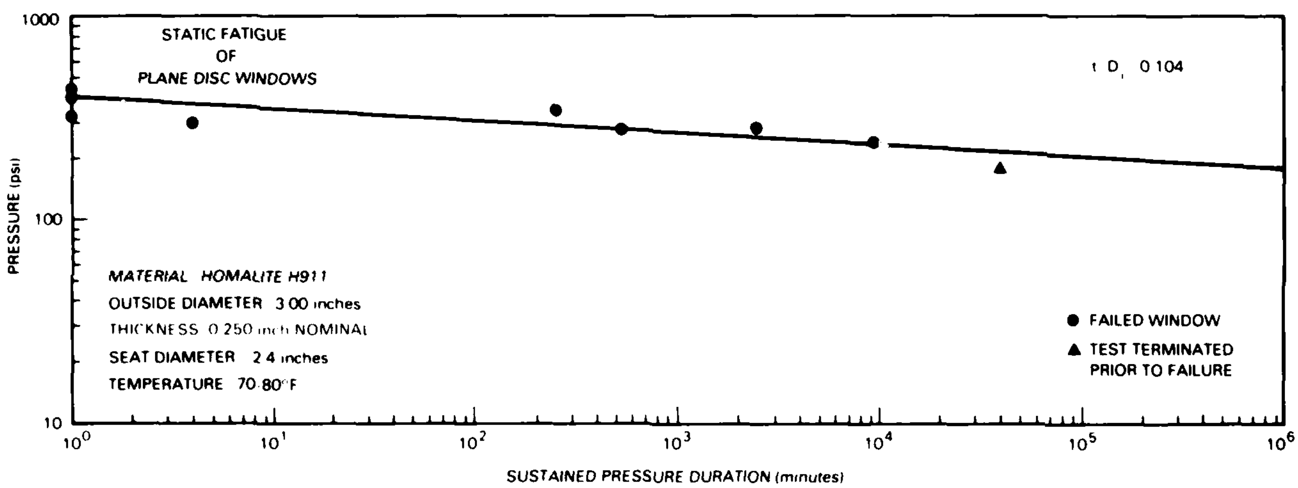

Figure 27. Static fatigue of plane disc CR-39 plastic windows with t/D_i = 0.104 at ambient temperatures in the 70-80°F range.

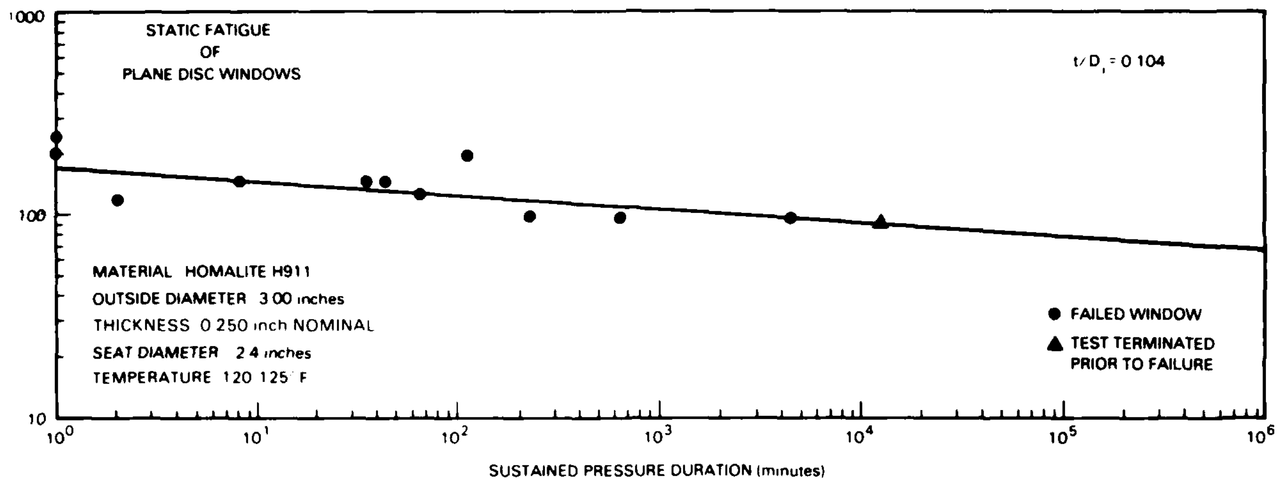

Figure 28. Static fatigue of plane disc CR-39 plastic windows with t/D_i = 0.104 at ambient temperatures in the 120-125°F range.

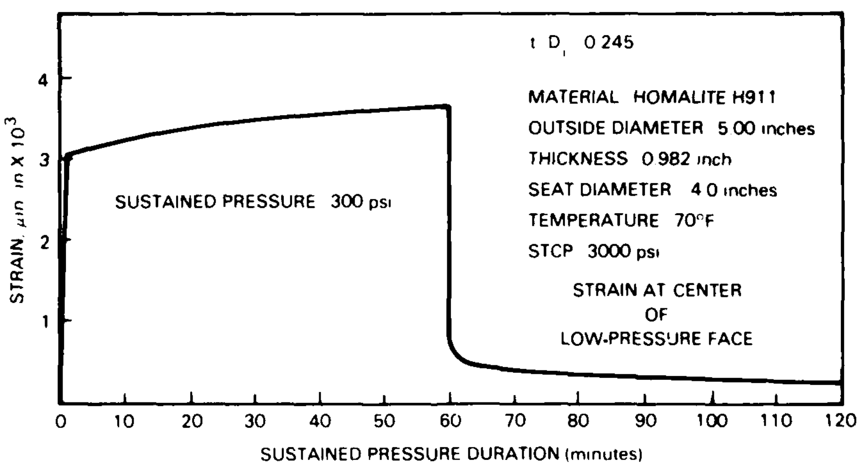

Figure 29. Strain at the center of the low-pressure face on plane disc CR-39 plastic window with t/D_i = 0.245 during the pressure cycle. The maximum pressure during sustained loading is equal to 10 percent of the window's STCP.

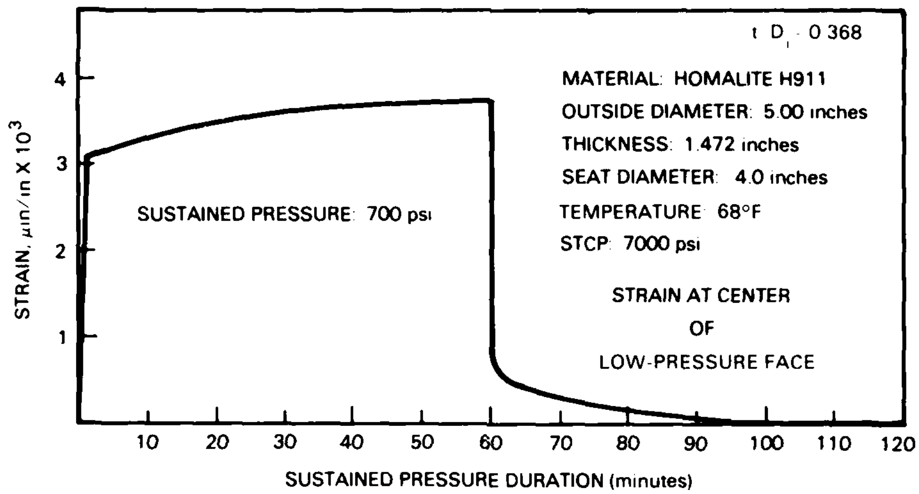

Figure 30. Strain at the center of the low-pressure face on plane disc CR-39 plastic window with $t/D_i = 0.368$ subjected to long-term pressure loading at 68°F. The maximum pressure during sustained loading is 10 percent of the window's STCP. Note that the strains relax completely after unloading.

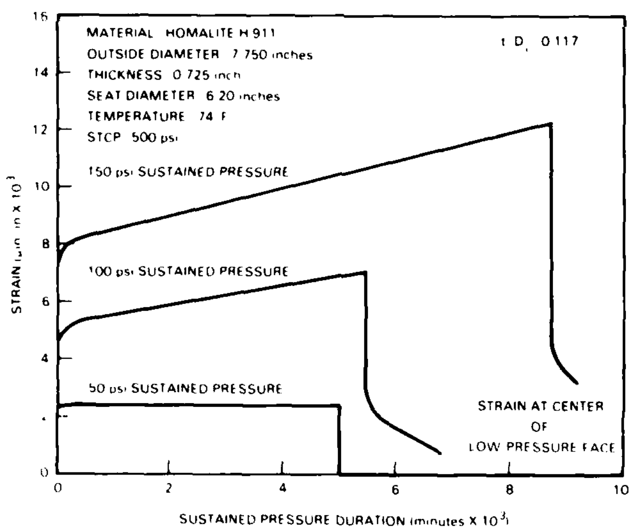

Figure 31. Strain at the center of the low-pressure face on plane disc CR-39 plastic window with 0.725-inch thickness and 6.2-inch unsupported diameter after different sustained pressure loadings at 74°F ambient temperature. Note that material creep occurs only at pressure loadings in excess of 0.1 STCP.

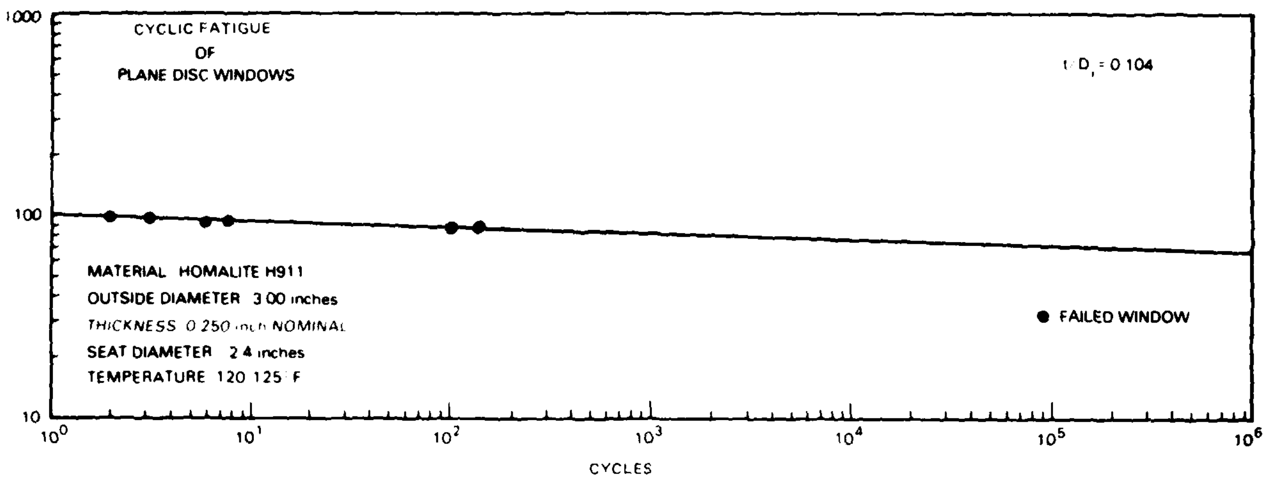

Figure 32. Cyclic fatigue of plane disc CR-39 plastic windows with t/D_i = 0.104 atambient temperatures in the 120-125°F range. Each cycle consists of 60-minute-long sustained pressure followed by 60 minutes of relaxation at 0 psi.

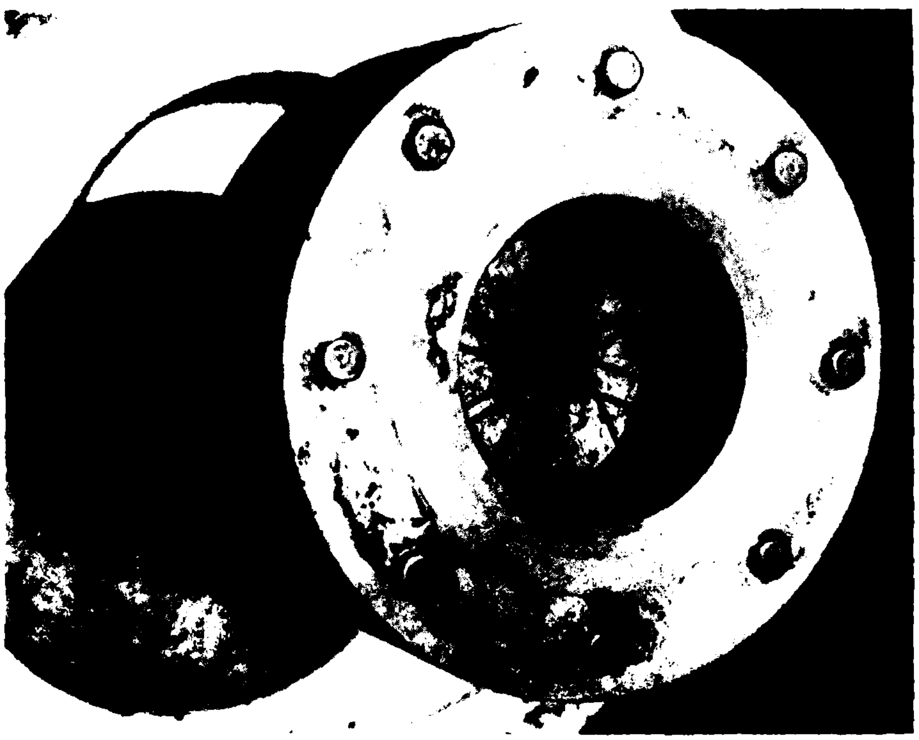

Figure 33. Notched CR-39 disc window with t/D_i = 0.104 mounted in the test fixture for 3-inch discs.

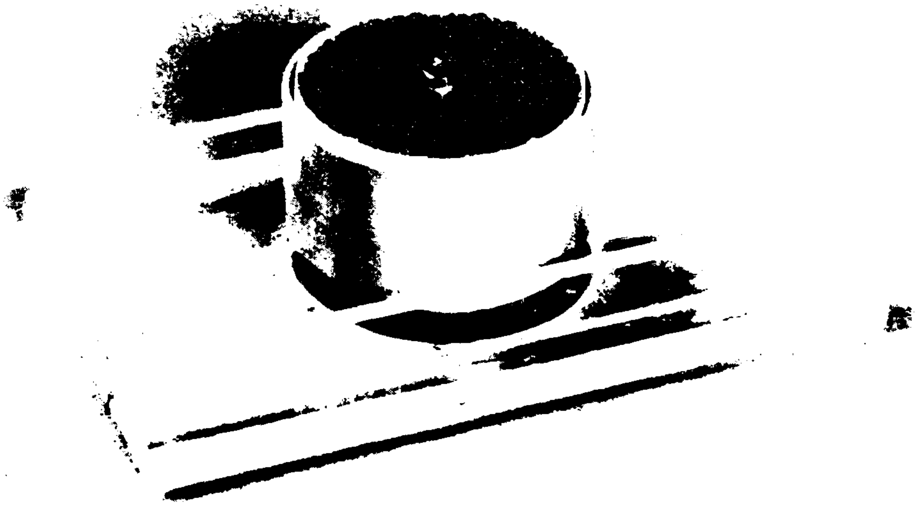

Figure 34a. Fixture for sanding of disc windows under controlled conditions, assembled.

Figure 34b. Fixture for sanding of disc windows under controlled conditions, disassembled.

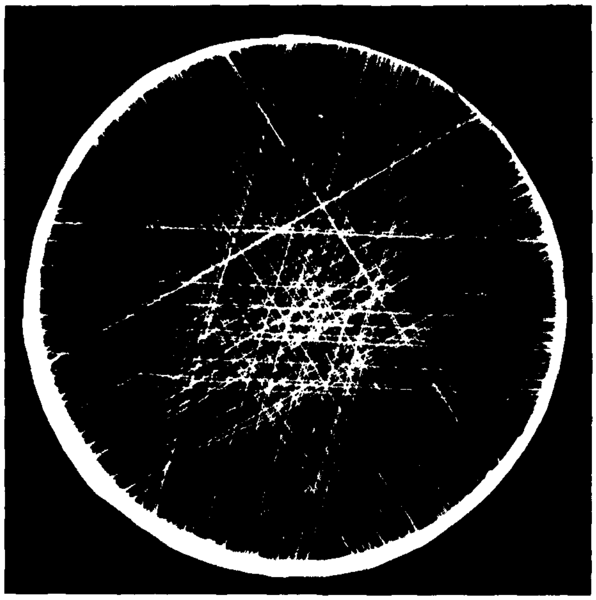

Figure 35. Acrylic plastic disc window after four strokes with a 1-inch-square pad of 80-grit sandpaper.

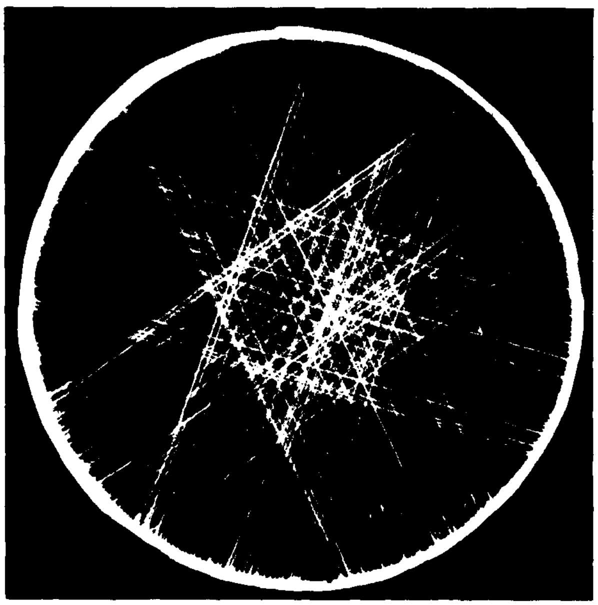

Figure 36. Acrylic plastic disc window after four strokes with a 1-inch-square pad of 150-grit sandpaper.

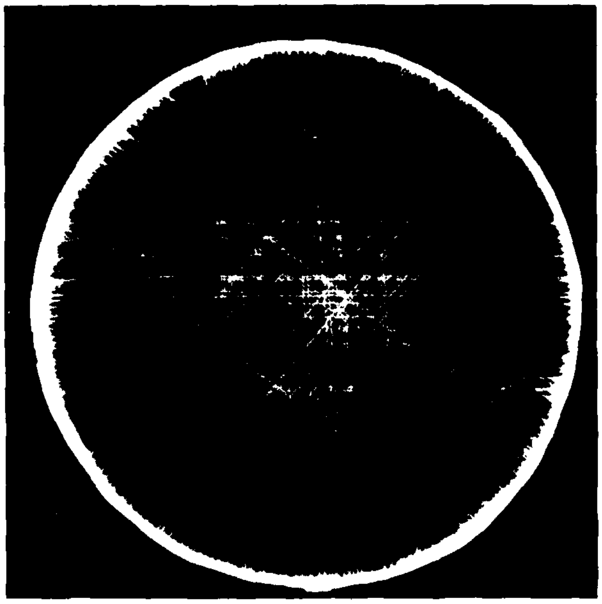

Figure 37. Acrylic plastic disc window after four strokes with a 1-inch-square pad of 200-grit sandpaper.

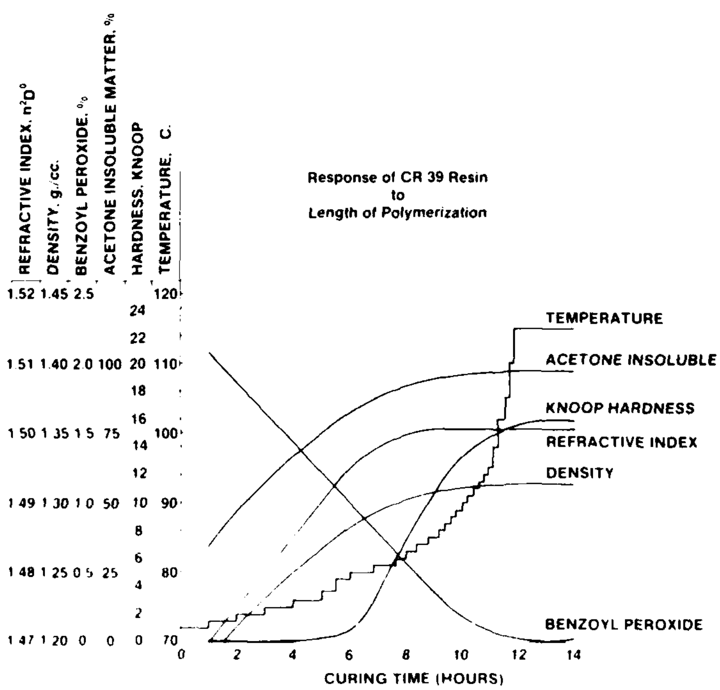

Figure 38. Effect of curing time and temperature on properties of CR 39 casting.

APPENDIX

Results of Hydrostatic Testing of CR-39 Flat Disc Windows

Table A-1. Tensile Strength of CR-39 Plastic Under Short-Term Loading.

SPECIFICATION: Homalite H. 911
TEST METHOD : ASTM D 638-82a

TENSILE ULTIMATE STRENGTH, MODULUS AND ELONGATION

RATE OF TEST: 0.20 INCHES/MINUTE

SPECIMEN	THICKNESS	WIDTH	MAXIMUM LOAD	ULTIMATE STRENGTH	TENSILE MODULUS	ELONGATION
	[-----inches-----]		pounds	---PSI--	PSIx10+4	--%--
MATERIAL I.D.: CR-39 PLASTIC						
TEST CONDITIONS :TESTED AT 100+-5 DEG. F AFTER 15 MINUTES AT 100+-5 DEG. F						
1	0.256	0.495	547	4,320	1.79	6.6
2	0.257	0.496	535	4,200	1.70	6.3
3	0.253	0.497	498	3,960	1.79	5.6
			AVERAGE =	4,160	1.76	6.2
			STANDARD DEVIATION =	183	0.052	0.51
			COEFFICIENT OF VARIATION =	4.40%	2.95%	8.23%
TEST CONDITIONS :TESTED AT 125+-5 DEG. F AFTER 15 MINUTES AT 125+-5 DEG. F						
1	0.248	0.498	313	2,530	9.10	5.2
2	0.254	0.499	339	2,670	9.48	6.0
3	0.247	0.500	328	2,660	9.53	5.9
			AVERAGE =	2,620	9.37	5.7
			STANDARD DEVIATION =	78	0.235	0.44
			COEFFICIENT OF VARIATION =	2.98%	2.51%	7.72%
TEST CONDITIONS :TESTED AT 150+-5 DEG. F AFTER 15 MINUTES AT 150+-5 DEG. F						
1	0.249	0.497	135	1,090	5.50	2.6
2	0.249	0.498	182	1,470	6.11	5.2
3	0.247	0.499	158	1,280	6.15	3.1
			AVERAGE =	1,280	5.92	3.6
			STANDARD DEVIATION =	190	0.364	1.38
			COEFFICIENT OF VARIATION =	14.84%	6.15%	38.33%

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Table A-1. Tensile Strength of CR-39 Plastic Under Short-Term Loading. (Contd)

SPECIFICATION:
TEST METHOD : ASTM D 638-82a

TENSILE ULTIMATE STRENGTH,MODULUS AND ELONGATION

RATE OF TEST: 0.20 INCHES/MINUTE

ECIMEN	THICKNESS	WIDTH	MAXIMUM LOAD	ULTIMATE STRENGTH	TENSILE MODULUS	ELONGATION
======	=========	=====	=======	========	=======	==========
	[-----inches	-----]	pounds	---PSI--	PSIx10+5	--%--
MATERIAL I.D.: CR-39 PLASTIC						
EST CONDITIONS :TESTED AT 32+-5 DEG. F AFTER 15 MINUTES AT 32+-5 DEG. F						
1	0.247	0.499	885	7,180	3.22	2.7
2	0.251	0.495	1,050	8,450	3.42	3.6
3	0.253	0.498	1,030	8,170	3.38	3.4
			AVERAGE =	7,930	3.34	3.2
		STANDARD DEVIATION =		667	0.106	0.47
		COEFFICIENT OF VARIATION =		8.41%	3.17%	14.69%
TEST CONDITIONS :TESTED AT 50+-5 DEG. F AFTER 15 MINUTES AT 50+-5 DEG. F						
1	0.248	0.496	832	6,760	3.04	2.8
2	0.249	0.497	816	6,590	3.06	2.6
3	0.254	0.497	830	6,570	2.98	2.8
			AVERAGE =	6,640	3.03	2.7
		STANDARD DEVIATION =		104	0.041	0.12
		COEFFICIENT OF VARIATION =		1.57%	1.38%	4.44%
'EST CONDITIONS :TESTED AT ROOM TREMPERATURE (75+-5 DEG. F)						
1	0.252	0.496	662	5,300	2.40	3.6
2	0.250	0.498	710	5,700	2.48	4.9
3	0.250	0.497	649	5,220	2.48	3.1
			AVERAGE =	5,410	2.45	3.9
		STANDARD DEVIATION =		257	0.046	0.93
		COEFFICIENT OF VARIATION =		4.75%	1.89%	23.85%

Note: 1. The test specimens were machined from 0.25-inch-thick CR-39 sheet casting procured from Homalite Inc. as H-911 composition.
2. Hardness tests performed on the sheet indicate that the casting was totally polymerized as specified by the purchase order to the vendor.

Table A-2. STCP of 3-Inch Flat Disc CR-39 Plastic Windows.

Specimen	Outside Diameter, inches	Thickness, inches	Temperature, °F	Critical Pressure, psi
1	2.985	0.226	47	947
2	2.985	0.234	44	880
3	2.985	0.230	46	660
4	2.985	0.229	46	840
5	2.985	0.231	45	710
Summary: min 660 psi; av 807 psi; max 947 psi				
6	2.985	6.250	80	550
7	2.983	0.248	80	670
8	2.983	0.247	80	640
9	2.985	0.250	80	400
10	2.985	0.256	80	380
11	2.985	0.256	80	460
12	2.985	0.260	80	580
13	2.985	0.260	76	780
Summary: min 380 psi; av 557 psi; max 780 psi				
14	2.985	0.242	125	240
15	2.985	0.242	118	370
16	2.985	0.242	116	320
17	2.982	0.245	117	342
18	2.984	0.243	115	330
Summary: min 240 psi; av 320 psi; max 370 psi				

NOTES: 1. Windows were seated on 2.40-inch-inside-diameter aluminum seat covered with 0.02-inch-thick Fairprene gasket.
2. Pressure rise was in the 500 to 700 psi/minute range.

Table A-3. STCP of 5-Inch Flat Disc CR-39 Plastic Windows.

Specimen	Outside Diameter, inches	Thickness, inches	Temperature, °F	Critical Pressure, psi
1	5.00	1.000	70	3,000
2	5.00	0.992	71	3,500
3	5.00	0.992	70	3,300
4	5.00	0.992	70	2,100
5	5.00	0.982	70	2,000
Summary: min 2,000 psi; av 3,380 psi; max 3,500 psi				
6	5.00	1.195	70	5,800
7	5.00	1.195	71	4,400
8	5.00	1.250	70	3,500
9	5.00	1.117	70	4,000
10	5.00	1.220	70	3,600
Summary: min 3,500 psi; av 4,260 psi; max 5,800 psi				
11	5.00	1.469	69	6,600
12	5.00	1.484	72	6,500
13	5.00	1.484	72	7,700
14	5.00	1.484	70	7,000
15	5.00	1.472	68	6,250
Summary: min 6,250 psi; av 6,810 psi; max 7,700 psi				
16	5.00	1.609	70	7,500
17	5.00	1.750	69	9,000
18	5.00	1.688	70	8,000
19	5.00	1.703	69	8,000
20	5.00	1.735	70	8,700
Summary: min 7,500 psi; av 8,240 psi; max 9,000 psi				
21	5.00	1.656	132	5,900
22	5.00	1.644	132	5,700
23	5.00	1.727	132	6,500
24	5.00	1.719	132	6,250
25	5.00	1.711	130	7,000
Summary: min 5,700 psi; av 6,270 psi; max 7,000 psi				
26	5.00	1.969	70	15,000
27	5.00	1.961	70	14,500
28	5.00	2.000	70	15,000
29	5.00	2.039	70	15,000
30	5.00	1.965	70	15,000
Summary: min 14,500 psi; av 14,900 psi; max 15,000 psi				

NOTES: 1. Windows were seated on 4.00-inch-inside-diameter steel seat, covered with 60-Durometer-hardness, 0.063-inch-thick neoprene gasket.
2. Pressure rise was in the 500 to 600 psi/minute range.

Table A-4. STCP of 7.75-Inch Flat Disc CR-39 Plastic Windows.

Specimen	Outside Diameter, inches	Thickness, inches	Temperature, °F	Critical Pressure, psi
1	7.75	0.455	38	120
2	7.75	0.435	40	200
3	7.75	0.461	38	170
4	7.75	0.445	40	170
5	7.75	0.458	39	180
Summary: min 120 psi; av 168 psi; max 200 psi				
6	7.75	0.498	82	218
7	7.75	0.495	78	380
8	7.75	0.492	78	460
9	7.75	0.492	80	260
10	7.75	0.492	80	260
Summary: min 218 psi; av 315 psi; max 460 psi				
11	7.75	0.470	80	560
12	7.75	0.465	80	290
13	7.75	0.480	83	370
14	7.75	0.463	83	320
15	7.75	0.475	81	300
Summary: min 290 psi; av 368 psi; max 560 psi				
16	7.75	0.487	110	90
17	7.75	0.473	110	110
18	7.75	0.475	110	80
19	7.75	0.480	110	180
20	7.75	0.482	109	120
Summary: min 80 psi; av 116 psi; max 180 psi				
21	7.75	0.732	70	300
22	7.75	0.725	72	500
23	7.75	0.725	72	484
24	7.75	0.730	74	420
25	7.75	0.735	73	440
Summary: min 300 psi; av 429 psi; max 500 psi				
26	7.75	1.008	72	1550
27	7.75	0.971	72	1520
28	7.75	1.000	73	1850
29	7.75	0.982	75	1200
30	7.75	0.995	72	1480
Summary: min 1200 psi; av 1520 psi; max 1850 psi				

NOTES: 1. Windows were seated on 6.20-inch-inside-diameter steel seat, covered with 60-Durometer-hardness, 0.063-inch-thick neoprene gasket.
2. Pressure rise was in the 500 to 700 psi/minute range.

Table A-5. STCP of 7.75-Inch Flat Disc Acrylic Plastic Windows.

Specimen	Outside Diameter, inches	Thickness, inches	Temperature, °F	Critical Pressure, psi
1	7.750	0.470	38	500
2	7.750	0.465	40	350
3	7.750	0.465	40	375
4	7.750	0.475	40	375
5	7.750	0.471	40	400
Summary: min 350 psi; av 400 psi; max 500 psi				
6	7.750	0.470	80	540
7	7.750	0.465	80	290
8	7.750	0.480	83	480
9	7.750	0.463	82	320
10	7.750	0.469	78	560
Summary: min 290 psi; av 438 psi; max 560 psi				
11	7.750	0.465	118	320
12	7.750	0.460	110	460
13	7.750	0.468	110	300
14	7.750	0.465	110	270
15	7.750	0.469	111	300
Summary: min 270 psi; av 330 psi; max 460 psi				

NOTES: 1. Windows were seated on 6.20-inch-inside-diameter steel seat, covered with 60-Durometer-hardness, 0.063-inch-thick Neoprene gasket.

2. Pressure rise was in the 500 to 700 psi/minute range.

Table A-6. Strain at Center of Flat Disc CR-39 Plastic Window.

Outside Diameter: 5.00 inches

Thickness: 0.982 inch

Temperature: 70° F

Seat Diameter: 4.00 inches

Bearing Gasket: 60-Durometer, 0.063-inch-thick Neoprene

	Time, minutes	Pressure, psi	Maximum Strain, microinches/inch
PRESSURIZED	0	0	0
		100	+990
		200	+2100
	1	300	+3010
	15	300	+3300
	30	300	+3500
	45	300	+3590
	60	300	+3680
UNPRESSURIZED	0	0	+ 700
	15	0	+ 380
	30	0	+ 300
	45	0	+ 240
	60	0	+ 100
	75	0	+ 53
	105	0	+ 16
	110	0	+ 0
	120	0	+ 0

NOTE: Under short-term loading, the window cracked at 650 psi and imploded at 2,000 psi.

Table A-7. Strain at Center of Flat Disc CR-39 Plastic Window.

Outside Diameter: 5.00 inches

Thickness: 1.220 inches

Temperature: 72°F

Seat Diameter: 4.00 inches

Bearing Gasket: 60-Durometer, 0.063-inch-thick Neoprene

	Time, minutes	Pressure, psi	Maximum Strain, microinches/inch
PRESSURIZED	0	0	0
		100	+ 630
		200	+1380
		300	+1930
		400	+2580
	1	440	+2650
	15	440	+2060
	30	440	+2060
	45	440	+2060
	60	440	+2060
UNPRESSURIZED	0	0	+ 170
	15	0	- 150
	30	0	- 200
	45	0	- 250
	60	0	- 300

NOTE: Under short-term loading, the window cracked at 1,000 psi and imploded at 3,600 psi.

Table A-8. Strain at Center of Flat Disc CR-39 Plastic Window.

Outside Diameter: 5.00 inches

Thickness: 1.472 inches

Temperature: 68° F

Seat Diameter: 4.00 inches

Bearing Gasket: 60-Durometer, 0.063-inch-thick Neoprene

	Time, minutes	Pressure, psi	Maximum Strain, microinches/inch
PRESSURIZED	0	0	0
		100	+ 700
		200	+1400
		300	+2200
		400	+2760
		500	+3100
		600	+2700
	1	700	+3110
	15	700	+3350
	30	700	+3710
	45	700	+3760
	60	700	+3790
UNPRESSURIZED	1	0	+ 760
	15	0	+ 220
	30	0	+ 60
	45	0	+ 10
	60	0	- 10

NOTE: Under short-term loading, the window cracked at 2,000 psi and imploded at 6,250 psi.

Table A-9. Strain at Center of Flat Disc CR-39 Plastic Window.

Outside Diameter: 5.00 inches

Thickness: 1.735 inches

Temperature: 70° F

Seat Diameter: 4.00 inches

Bearing Gasket: 60-Durometer, 0.063-inch-thick Neoprene

	Time, minutes	Pressure, psi	Maximum Strain, microinches/inch
PRESSURIZED	0	0	
		100	+ 300
		200	+ 500
		300	+ 700
		400	+ 900
		500	+1100
		600	+1400
		700	+1700
	2	800	+1900
	15	800	+2000
	30	800	+2020
	45	800	+2020
	60	800	+2040
UNPRESSURIZED	1	0	+ 220
	15	0	- 60
	30	0	- 10
	45	0	0
	60	0	0

NOTE: Under short-term loading, the window cracked at 4,000 psi and imploded at 8,700 psi.

Table A-10. Strain at Center of Flat Disc CR-39 Plastic Window.

Outside Diameter:	5.00 inches
Thickness:	1.965 inches
Temperature:	70°F
Seat Diameter:	4.00 inches
Bearing Gasket:	60-Durometer, 0.063-inch-thick Neoprene

	Time, minutes	Pressure, psi	Maximum Strain, microinches/inch
PRESSURIZED	0	0	0
		200	480
		300	670
		400	850
		500	1010
		600	1200
		700	1470
		800	1660
		900	1790
		1000	1900
		1100	2090
		1200	2220
		1300	2360
		1400	2530
	2	1500	2680
	15	1500	2710
	30	1500	2690
	45	1500	2550
	60	1500	2550
UNPRESSURIZED	1	0	+ 80
	15	0	-560
	30	0	-700
	45	0	-740
	60	0	-800

NOTE: Under short-term loading the window cracked at 8,200 psi and imploded at 15,000 psi.

Table A-11. Strain at Center of Flat Disc CR-39 Plastic Window.

Outside Diameter: 7.750 inches

Thickness: 0.460 inch

Temperature: 71° F

Seat Diameter: 6.2 inches

Bearing Gasket: None

	Time, minutes	Pressure, psi	Maximum Strain, microinches/inch
PRESSURIZED	0	0	000
		10	+1030
		20	+1700
	1	30	+2200
	4	30	+2320
	10	30	+2330
	60	30	+2330
UNPRESSURIZED	0	0	+ 300
	7	0	30
	15	0	6
	60	0	0

Table A-12. Strain at Center of Flat Disc CR-39 Plastic Window.

Outside Diameter:	7.750 inches
Thickness:	0.460 inch
Temperature:	94° F
Seat Diameter:	6.2 inches
Bearing Gasket:	None

	Time, minutes	Pressure psi	Maximum Strain, microinches/inch
	0	0	000
		10	+ 1100
		20	+ 1780
PRESSURIZED	0	30	+ 2770
	15	30	+ 2817
	19	30	+ 2815
	22	30	+ 2806
DEPRESSURIZED	0	0	+ 700
	3	0	+ 115
	9	0	+ 12
	12	0	0

Table A-13. Strain at Center of Flat Disc CR-39 Plastic Window.

Outside Diameter: 7.750 inches

Thickness: 0.460 inch

Temperature: 108°F

Seat Diameter: 6.2 inches

Bearing Gasket: None

	Time, minutes	Pressure, psi	Maximum Strain, microinches/inch
PRESSURIZED	0	0	+ 000
		10	+1200
		20	+1950
	1	30	+2600
	2	30	+2880
	5	30	+2950
	8	30	+3000
	10	30	+3040
	12	30	+3087
	23	30	+3167
	33	30	+3186
DEPRESSURIZED	0	0	
	2	0	+ 900
	13	0	+ 421
	30	0	+ 260

Table A-14. Strain at Center of Flat Disc CR-39 Plastic Window.

Outside Diameter: 7.750 inches

Thickness: 0.460 inch

Temperature: 71° F

Seat Diameter: 6.2 inches

Bearing Gasket: None

	Time, minutes	Pressure, psi	Maximum Strain, microinches/inch
PRESSURIZED	0	0	+ 000
		10	+0740
		20	+1350
		30	+2200
		40	+3000
	3	50	+3850
	5	50	+4093
	10	50	+4140
	15	50	+4160
	150	50	+4230
	1200	50	+4560
UNPRESSURIZED	0	0	+3500
	3	0	+ 470
	5	0	+ 356
	1200	0	- 177

Table A-15. Strain at Center of Flat Disc CR-39 Plastic Window.

Outside Diameter: 7.750 inches

Thickness: 0.460 inch

Temperature: 72° F

Seat Diameter: 6.2 inches

Bearing Gasket: None

	Time, minutes	Pressure, psi	Maximum Strain, microinches/inch
PRESSURIZED	0	0	000
		10	+1010
		20	+1560
		30	+2180
		40	+2900
		50	+3600
		60	+4400
	1	70	+5200
	2	70	+5460
	7	70	+5615
	35	70	+5691
	60	70	+5700
DEPRESSURIZED	0	0	+1500
	3	0	+ 480
	5	0	+ 300
	10	0	+ 198
	144	0	+ 35

Table A-16. Strain at Center of Flat Disc CR-39 Plastic Window.

Outside Diameter: 7.750 inches

Thickness: 0.460 inch

Temperature: 71° F

Seat Diameter: 6.2 inches

Bearing Gasket: None

	Time, minutes	Pressure, psi	Maximum Strain, microinches/inch
PRESSURIZED	0	0	0
		20	+2000
		40	+2920
		60	+4660
		80	+6250
	3	100	+7940
	15	100	+9120
	45	100	+9270
	60	100	+9230
	240	100	+9500
UNPRESSURIZED	0	0	+2900
	5	0	+1130
	20	0	+ 560
	35	0	+ 387
	60	0	+ 256
	180	0	+ 001

Table A-17. Strain at Center of Flat Disc CR-39 Plastic Window.

Outside Diameter: 7.750 inches

Thickness : 0.725 inch

Temperature: 74° F

Seat Diameter: 6.20 inches

Bearing Gasket: 60-Durometer, 0.063-inch-thick Neoprene

	Time, minutes	Pressure, psi	Maximum Strain, microinches/inch
PRESSURIZED	0	0	000
		10	+ 460
		20	+ 950
		30	+1385
		40	+2006
	1	50	+2300
	5	50	+2348
	45	50	+2445
	85	50	+2420
	150	50	+2380
	210	50	+2400
UNPRESSURIZED	0	0	+ 000
	1	0	+ 130
	180	0	- 16

Table A-18. Strain at Center of Flat Disc CR-39 Plastic Window.

Outside Diameter: 7.750 inches

Thickness: 0.725 inch

Temperature: 74 ° F

Seat Diameter: 6.20 inches

Bearing Gasket: 60-Durometer, 0.063-inch-thick Neoprene

	Time, minutes	Pressure, psi	Maximum Strain, microinches/inch
PRESSURIZED	0	0	000
		10	+ 580
		20	+1230
		30	+1310
		40	+2070
		50	+2370
		60	+2654
		70	+3104
		80	+3600
		90	+4010
	3	100	+4475
	5	100	+4676
	7	100	+4718
	13	100	+4733
	25	100	+4858
	70	100	+4941
	240	100	+5196
	1860	100	+5903
	2600	100	+6162
	4650	100	+6735
	5500	100	+7145
UNPRESSURIZED	0	0	+2890
	300	0	+1860
	1260	0	+ 860

Table A-19. Strain at Center of Flat Disc CR-39 Plastic Window.

Outside Diameter: 7.750 inches

Thickness: 0.725 inch

Temperature: 72 ° F

Seat Diameter: 6.20 inches

Bearing Gasket: 60-Durometer, 0.063-inch-thick Neoprene

	Time, minutes	Pressure, psi	Maximum Strain, microinches/inch
PRESSURIZED	0	0	+000
		10	+930
		20	+1005
		30	+1500
		40	+1761
		50	+2400
		60	+2950
		70	+3280
		80	+3750
		90	+4162
		100	+4550
		110	+5090
		120	+5500
		130	+5960
		140	+6455
	3	150	+6935
	5	150	+7310
	20	150	+7612
	80	150	+7869
	525	150	+8351
	8750	150	+12300
UNPRESSURIZED	0	0	+6400
	15	0	+4765
	165	0	+3844
	465	0	+3235

Table A-20. Strain at Center of Flat Disc CR-39 Plastic Window.

Outside Diameter:	7.750 inches
Thickness:	0.725 inch
Temperature:	74 ° F
Seat Diameter:	6.20 inches
Bearing Gasket:	60-Durometer, 0.063-inch-thick Neoprene

	Time, minutes	Pressure, psi	Maximum Strain, microinches/inch
PRESSURIZATION	0	0	000
		10	+620
		20	+900
		30	+1420
		40	+1720
		50	+2160
		60	+2540
		70	+2970
		80	+3350
		90	+3880
		100	+4260
		120	+5090
		140	+6090
		160	+6880
		180	+7780
		200	+8790
		220	+9680
		240	+10490
		260	+11380
		280	+12300
		300	+13580
		320	+14480
		340	+14990
		360	+15980
		380	+17040
		400	+17900
		500	+23830
	6	520	+26640 Implosion

Table A-21. 3-Inch-Diameter Flat Disc CR-39 Plastic Windows Under Long-Term Pressurization.

pecimen	Outside Diameter, inches	Thickness, inches	Temperature, °F	Pressure, psi	Time at Failure, minutes
1	2.988	0.245	75	300	600
2	2.985	0.227	80	300	548
3	2.988	0.237	80	350	286
4	2.988	0.237	75	400	0.5
5	2.988	0.227	120	250	0.5
6	2.985	0.233	120	200	108
7	2.985	0.230	120	200	10.75
8	2.987	0.228	120	200	0.1
9	2.985	0.249	120	200	0.8
10	2.982	0.237	120	150	8
11	2.986	0.242	118	150	34
12	2.985	0.237	120	130	62
13	2.980	0.236	120	130	41
14	2.984	0.230	120	100	630
15	2.986	0.236	120	100	224
16	2.985	0.224	120	100	940
17	2.983	0.240	120	100	4710
18	2.988	0.241	125	120	2
19	2.987	0.231	117	100	11760

OTES: 1. Windows were seated on 2.40-inch-inside-diameter aluminum seat covered with 0.02-inch-thick Fairprene gasket.

2. The pressurization medium was heated tap water.

Table A-22. 3-Inch-Diameter Flat Disc CR-39 Plastic Windows Under Cyclic Pressurization.

Specimen	Outside Diameter, inches	Thickness, inches	Temperature, °F	Pressure, psi	Cycles to Failure
1	2.985	0.238	125	100	6
2	2.985	0.240	125	100	3
3	2.985	0.241	125	80	150
4	2.983	0.242	125	80	106
5	2.987	0.247	125	100	1
6	2.986	0.238	125	100	8

NOTES:
1. Windows were seated on an aluminum seat (2.40-inch-inside-diameter, 3.0-inch-outside-diameter) covered by a 0.02-inch-thick Fairprene gaskets.
2. The typical pressure cycle consisted of pressurizing to maximum pressure at 650 psi/minute and maintaining the pressure for 60 minutes, depressurizing to zero at 650 psi/minute, and relaxing at zero pressure for 60 minutes.

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